

# **Turbocharger Deposits and Engine Deposits – A Duality: Correlative Bench Test Studies of Turbocharger Deposits**

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## **Abstract**

Use of turbochargers to improve small engine response and fuel efficiency is growing rapidly and requiring proper engine oil formulation to prevent a type of deposit similar to coke from forming after the engine is shut off. The TEOST 33C instrument and test was developed to simulate turbocharger operation and this paper is a world study of present engine oils regarding their response to this turbocharger-simulating deposit test.

## **Introduction and Background**

The personal automobile and its accoutrements have taken many forms over the years in which the automobile has served civilization for both work and pleasure. Today, its rate of change and development has never been faster as the demands of civilization have risen with its needs and with the number of automobile producers.

These changes and demands have been especially evident in the engine's primary power plant, the reciprocating engine. Today, in the quest to extract more power and performance with more fuel efficiency from the engine, its size has contracted but the power and performance have been maintained by various improvements such as greater use of the turbocharger – at an earlier time found only in the more exotic vehicles, racing machines, and so-called 'hot-rods'.

However, every change made by engine designers to extract more power while simultaneously curbing the fuel appetite of the engine brings more demands on the engine oil. One of these areas of demand is in mating the dual appetites of the engine and the turbocharger regarding resistance to oxidation. Contrary to many expectations that 'oxidation is oxidation is oxidation' in an engine oil, the fact is that the process of oxidation is not the same in the engine as in the turbocharger as this paper will show.

## **Comparison of the Oxidation Environments**

**Engine** – The general chemical mechanism of engine oil oxidation is reasonably well understood today although the availability of new additives and base oils continues to modify the oxidation process. Essentially, the mechanism is viewed as a process of exposing the engine oil at several temperatures ranging from sump temperature to ring-belt temperatures. Under these temperature conditions, a chemical and thermal attack occurs in the accumulating presence of both 'hard' inorganic acids such as hydrochloric, nitric and sulfuric and the various 'soft' organic acids all in the presence of engine wear metals capable of catalyzing oxidation response. The former acids encourage formation of the latter acids and the latter acids encourage the formation of varnish and deposits in conjunction with water normally present in the engine-adverse chemical conditions of short-trip driving.

**Turbocharger** – The primary role of the turbocharger is to force the engine to deliver more power and performance while the turbocharger extracts operating power from the waste energy pouring down the exhaust pipe. Lubrication of the turbocharger is by the engine oil – in whatever condition that oil is in as a consequence of its exposure to engine conditions.

However, the environment that the turbocharger provides the engine oil is considerably different than that which the oil encounters in the engine. First of all, it is a much simpler environment regarding conditions of oxidation – although the oil does carry the chemistry of the engine with it in its path through the turbocharger.

Secondly, the turbocharger environment encountered by the engine oil in its task of lubricating the turbocharger shaft bearings sketched in Figure 1 can be several hundred degrees hotter than any engine temperature. The heat of the turbine wheel and shaft exposed to the over 650 °C exhaust stream bleeds through the shaft to the shaft bearings as shown by the red arrow where at temperatures of 500 °C and higher [1,2] it contacts the engine oil being pumped through the bearings. As it lubricates the bearings, the engine oil also carries some of the heat of the turbine shaft away as the oil is also further oxidized by the heat to a degree reflecting the chemical condition of the oil being circulated in the engine.

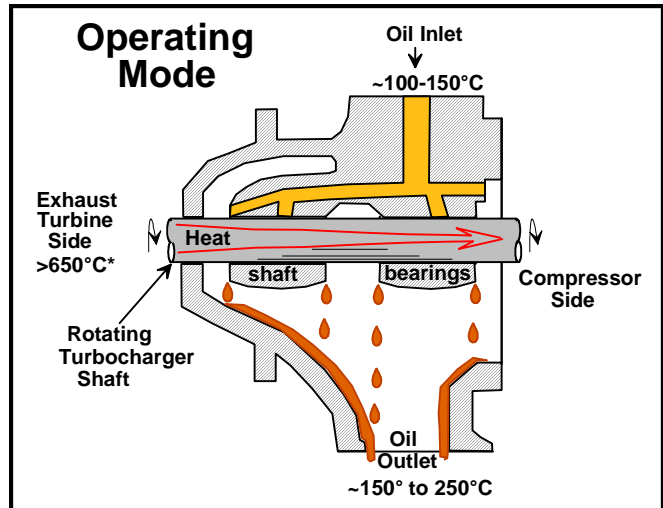


Fig. 1 – Simplistic sketch of an operating turbocharger showing the oil circulation and heat path through the shaft.

**‘Coking’ of the Engine Oil** – The critical point affecting both the oil and the turbocharger arrives when the engine is shut off after the turbocharger has been under rigorous use for some period of engine operation. At this point, the oil no longer circulates through the shaft bearings to carry away the heat. Consequently, the full heat of the turbocharger shaft is imposed on the bearing area and the relatively small volume of oil in the bearings and galleys immediately adjacent as shown in Fig. 2.

At these temperatures, the oil seems to respond much differently than at the much lower temperatures experienced in the engine. Depending on oil formulation and the extent of its usage in the engine and turbocharger, oxidation of the engine oil in the turbocharger may form a hard, somewhat porous, coke-like carbonaceous mass in the galleys. In time, this coke formation plugs the galleys as shown in Figure 2 causing failure.

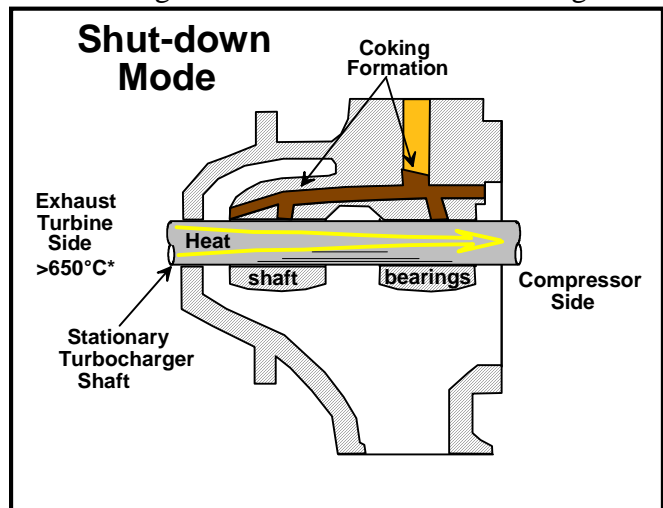


Fig. 2 – Same sketch as in Figure 1 with the consequences of progressive coke formation after turbocharger shutdown.

**Mechanical Methods of Reducing Coking** – There are mechanical methods of offsetting turbocharger coking. After engine shut down, one method is to use an auxiliary pump to feed engine oil to the turbocharger bearings until the turbocharger turbine shaft has cooled sufficiently. This is an expensive approach and subject to other problems of maintenance

and potential sites of engine oil leakage. Another approach is to keep the engine idling for a recommended five minutes or more with unfortunate compromise of fuel efficiency.

**Bench Tests and Engine Oil Formulation** – The least expensive way of controlling turbocharger coking tendency is by knowledgeable formulation of engine oil. That is, by selection of additives and base oils much less susceptible to coke formation.

However, the challenge has been to develop such oils without the need to run difficult-to-reproduce engine/turbocharger tests to screen candidate formulations.

The most reasonable approach was a bench test

1. correlating with field turbocharger experience,
2. relatively simple to conduct,
3. unambiguous in results, and
4. relatively fast.

### The TEOST Test for Comparative Turbocharger Coking Tendencies of Engine Oils

Responding to field turbocharger coking problems, in 1989 the Chrysler Corporation commissioned development of a bench test which would correlate with four reference oils – both coking and non-coking – which were from Europe and North America.

The development of the instrument required considerable information on the process of turbocharger coking tendencies and the influence of engine exposure of the engine oil. However, the work was ultimately successful in giving clear distinction among the four identified reference oils as shown in Figure 3.

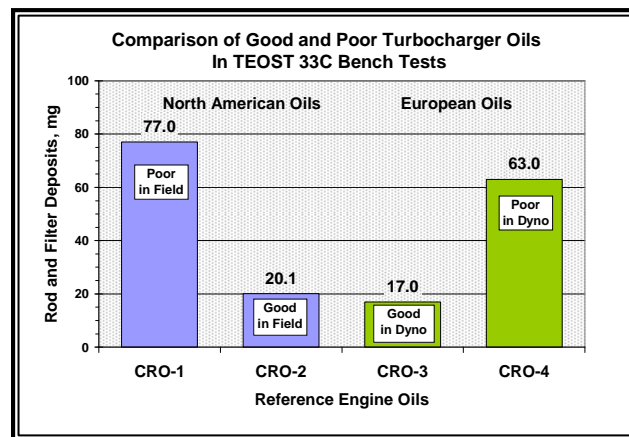
First publication of the TEOST 33C bench test development was in 1993 [2] and the work was awarded the Chrysler Corporation Technology Award of the year.

**The TEOST 33C Test Method** – After preliminary studies, a bench test instrument was designed for extensive work and subsequently modified for sharpening the results of the test.

As might be expected, the variables required for a turbocharger simulation test that was correlative but relatively short demanded extensive experimental work. Multiple protocols were tested and modified [3].

These protocols led to the design and application of an instrument called the Thermo-oxidation Engine Oil Simulation Test (TEOST) 33C by the Tannas Co., and was successful in producing the results shown in Figure 3 at an acceptable level of precision and test time.

Fig. 3 – Comparison of reference oils from Europe and North America using the TEOST 33C bench test.



In 1998 the method was approved after a preliminary round robin and became ASTM Standard Test Method D6335 [4]. The resulting TEOST 33C test instrument is shown in Figure 4.

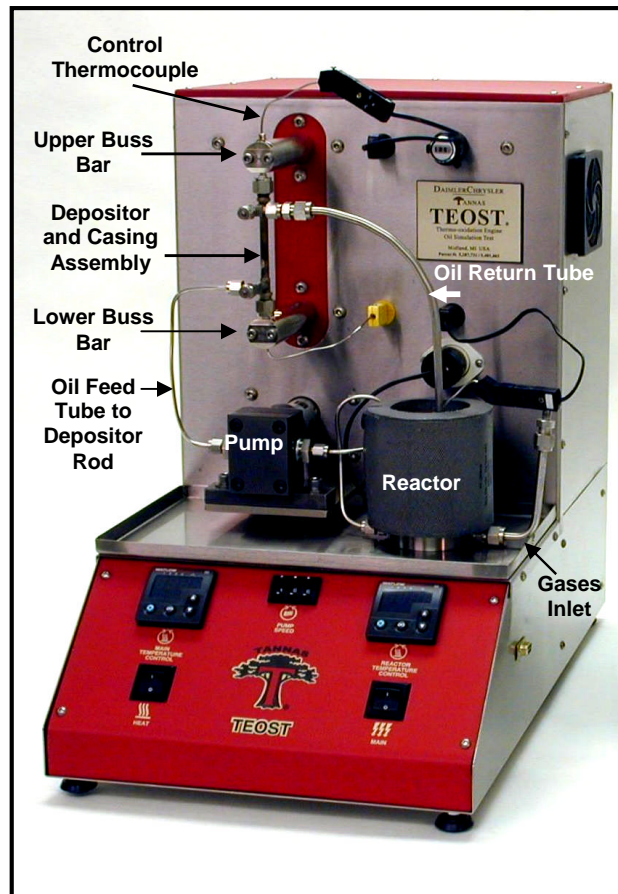


Fig. 4 –TEOST 33C bench test and components.

Following is a description of the salient portions of the protocol (more specific information may be gained through References [2] and [3]).

#### ***Stages of Test Oil Exposure in the TEOST 33C Instrument –***

***Engine Simulating Oxidation Environment*** – Test oil is preconditioned in the Reactor – roughly simulating exposure of the engine oil to bulk oxidation effects of the engine.

To accomplish this:

A 116 mL sample of the test oil containing 100 PPM soluble iron naphthenate (simulating the catalytic effects of the solid and soluble iron provided by the engine) is heated to, and closely controlled, at 100°C.

This test oil mixture is continuously stirred in the Reactor at this temperature. At the same time both water-saturated air and an oxide of nitrogen,  $N_2O^*$ , are introduced at the bottom of

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\* Nitrous oxide,  $N_2O$ , was chosen because it is easier to control during bench tests than nitric oxide,  $NO_2$ , (the more common product of combustion). However, at sufficiently high temperatures in the circulated oil, the former can decompose into the latter and, thus, accomplish the latter's role in engine oil decomposition.

the Reactor cup through the Gases Inlet shown in Figure 4 at a rate of 3.5 mL per minute into the stirred sample mixture. These gases are meant to simulate combustion chamber blow-by gases and the ongoing exposure of the engine oil to this environment at engine operating temperatures.

**Turbocharger Simulation** – The test oil mixture from the Reactor is continuously circulated by a calibrated, speed-controlled pump at 0.49 mL/minute through the Depositor and Casing Assembly stage of the TEOST 33C test, as shown in the cut-away sketch of Figure 5.

The heart of the TEOST 33C test is a carefully machined, hollow steel Depositor Rod upon which deposits are formed under the test conditions. The location of the hottest spot on the Depositor Rod is somewhat above the vertical center of its narrow neck as shown in Figure 5. (The reason for the above-center deposit location is that the test oil flowing into the Depositor Rod Casing must be heated from less than 100°C to the programmed, variable temperature of the Rod, discussed more fully below). The control thermocouple is precisely adjusted to this hottest spot on the Rod (by using of highly oxidation-resistant reference oil flowing through the Depositor Rod Casing Assembly to establish this position).

In contrast to some other oxidation tests based on visual color perception, the TEOST 33C turbocharger simulation test is based on careful gravimetric analysis of both the mass of deposit formed on the Depositor Rod plus the mass of deposits that have either fallen off the Rod or been generated otherwise in the circulating oil. Such gravimetric analysis frees the test from variable human judgment of deposit appearance or other indirect measurements that have been applied to oxidation tests over the years.

**12-Cycle Program** – When the test oil has been prepared for test and installed in the Reactor, the Pump is flushed with 10 mL of the test oil (subsequently discarded) and the test program initiated. Twelve cycles of the temperature program shown in Figure 6 are applied to the Depositor Rod to simulate severe operation and subsequent shutdown of the turbocharger<sup>†</sup>.

On completion of the twelve cycles, the test oil is carefully collected by draining and washing the Reactor, Pump, Depositor Assembly, and circulation lines. The Depositor Rod is then carefully removed from the Depositor Casing

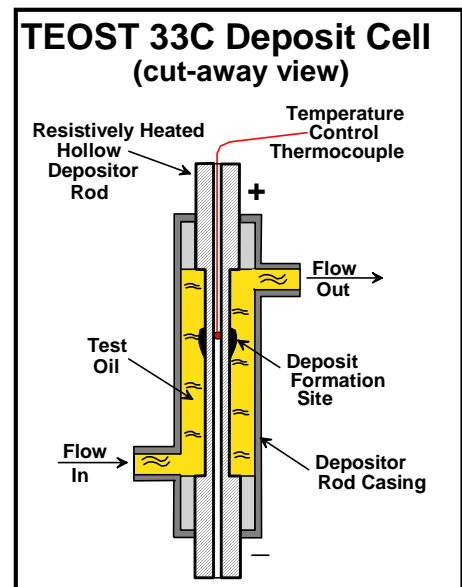


Fig. 5 – Sketch of Depositor Rod in Casing.

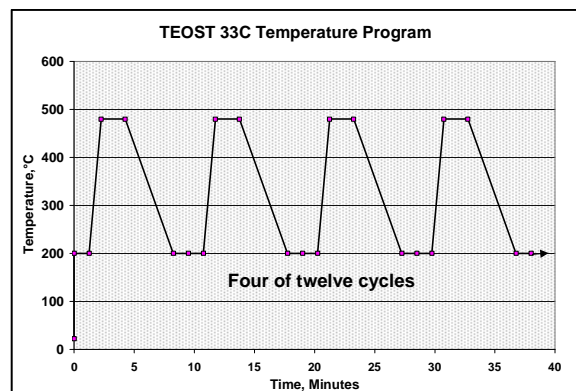


Fig. 6 – Cyclic temperature program imposed on Depositor Rod to simulate turbocharger deposit-forming conditions.

<sup>†</sup> The timed-temperature program is precisely imposed on the Depositor Rod. However, the response of the Rod and surrounding test oil produce temperature excursions depending on the nature of the oil and the resulting deposits.



Assembly and carefully washed into the collected test oil. Subsequently, the test oil is filtered and the Depositor Rod carefully dried and weighed. Increase in Filter and Depositor Rod weights in milligrams are combined as the test result.

## A Study of Engine Oils in the TEOST 33C Simulated Turbocharger Test

### Source of Comparative Data and Analytical Technique

Information from the Institute of Materials (IOM) Engine Oil Database (an extensive database on engine oils collected directly from the world's consumer markets for several decades) has included TEOST 33C data from 1996 to date. For this paper, it was considered pertinent to compare the performance of engine oils around the world from the years 2001, 2004, and 2008 in Europe, North America and Asia using this bench test.

To reduce such a mass of data to understandable and readily comparable form, distribution histograms of the TEOST 33C rod deposit data using 5 mg intervals from 5 to 95 mg were generated versus the percent of the oils analyzed falling into a given milligram deposit range for the indicated period of time.

### Additive Influences on Coking

Analysis of coke deposits from the turbocharger [3] indicated that this process might be initiated and/or supported by the response of certain additives or combination of additives to these very high temperature conditions – temperatures at and beyond which these additives are thermally responsive. This initial formation of a deposit 'bed' is then thought followed by further carbonaceous deposit of other components, particularly abetted by the base oil. Recent work by Yoshida and Naitoh [5] using only data obtained with their application of the TEOST tends to confirm the foregoing earlier view of deposit formation during.

In the reported work [3] of developing the TEOST, it was in fact speculated that absence of additives in oil might likely give low deposits. However, no data were available, of course.

### Engine Oils Essentially Without Additives

However, TEOST 33C data have been included in the IOM Engine Oil Database since 1996 and some few of these oils fell in the 'SA' API Service Class, indicating essentially additive-free engine oil. This provided the opportunity of determining the influence of additives in comparison with the data shown earlier in Figure 3.

Figure 7 shows the distribution histogram of the simulated turbocharger deposit level of the few marketed API SA oils collected for the IOM Database from 2001 to 2009.

The data show that 90 % of these oils fall below 12 mg in the TEOST 33C test. This low deposit level is clear evidence that at these very high coke-deposit-forming temperatures of the turbocharger, additives play a different role that at engine deposit formation temperatures. This was also the conclusion reached in the more recent TEOST studies reported [5] by Yoshida and Naitoh (although these authors, having no correlative turbocharger data, did not wish to extend their TEOST data to predict turbocharger deposits).

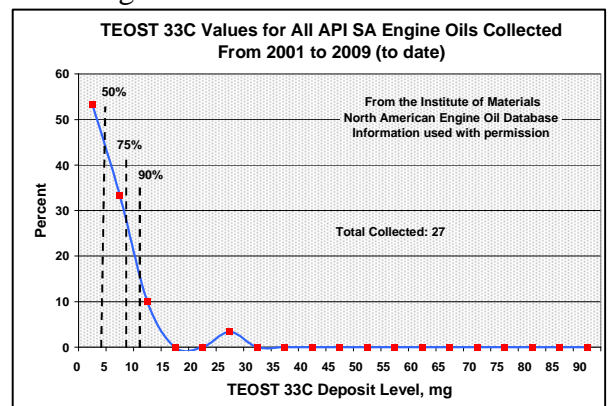


Fig. 7 – Histogram of bench test deposits of API SA oils.

Furthermore, the data shown in Figure 7 also underscore the evident distinction between the oxidation processes in the turbocharger which clearly show little response of these API SA oils – oils having no anti-oxidation additive protection – when compared to the engine oxidation environment. None of these API SA oils would be expected to perform well in engine oxidation tests or engine-simulating bench tests. (This is the subject of a second, forthcoming paper on the duality of turbocharger and engine oxidation tests.)

### Engine Oils in North America

Histograms for the years 2001, 2004, and 2008 are shown in Figure 8 (less than 0.1 % of these engine oils are non-additive-containing). For each of the histograms for these three years, the 90 percentile rod deposit value in the TEOST 33C test is shown by a vertical dashed line.

It is evident that oils collected in 2001 (where 90 % of the oils tested have less than 41 mg deposits) and 2004 (90 % of the oils tested have less than 44 mg deposits) are similar in the form of their respective histogram's distribution form. This suggests similar ranges of additive and base stock formulations. In contrast, 2008 shows a significant change in distribution to lower depositing oils and a related change in the 90 percentile value. This value is 36 mg – about 18% lower than that of 2004.

### Engine Oils in Europe

Analyses of the IOM Engine Oil Database for turbocharger-simulating deposit formation in the TEOST 33C test for engine oils collected throughout Europe are shown in Figure 9. Interestingly, the histogram for oils collected in 2001 showed considerably better control of such deposits than the later histograms of 2004 and 2008. The 90 percentile values of the latter two years were almost identical at a value of 40 mg compared to a value of 31 mg in 2001 although the shapes of the 2004 and 2008 histograms are not all that similar.

**Comparison of Histograms in 2008** – In regard to the forgoing observation, it may be noted that the 2008 histograms of both Europe and North America are quite similar in the deposit ranges below about 32 mg as shown in Figure 10. Again, this likely indicates a similar range of base stocks and, particularly,

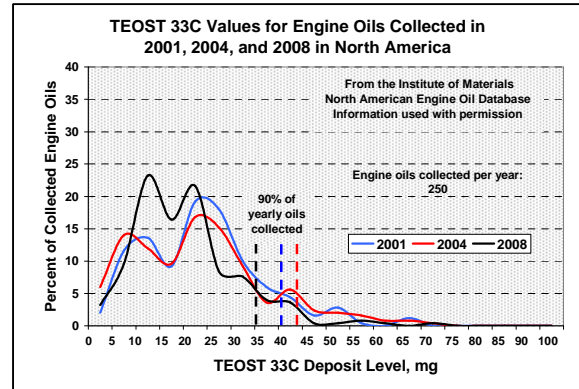


Fig. 8 – 2001, 2004, and 2008 histograms of bench test simulation of turbocharger deposits of North American engine oils.

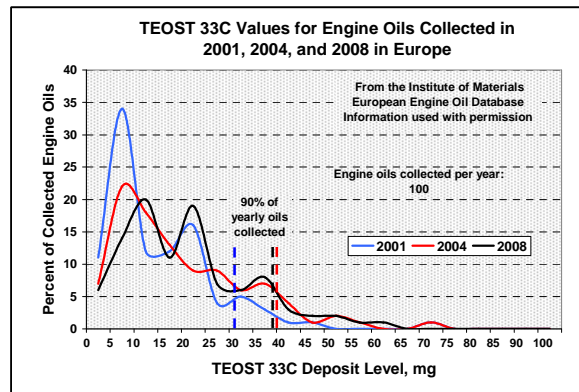


Fig. 9 – 2001, 2004, and 2008 histograms of bench test simulation of turbocharger deposits of European engine oils.

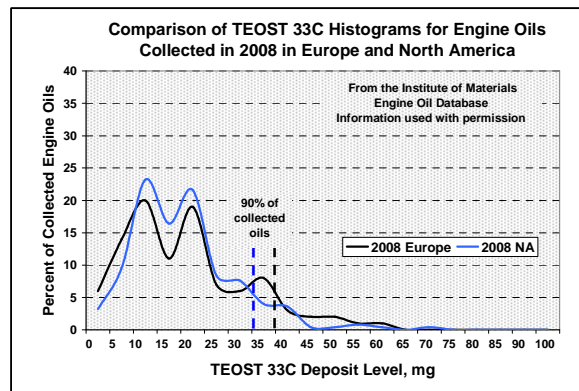


Fig. 10 – Comparison of histograms of year 2008 of both European and North American engine oils.

additive chemistries in both regions. However, different shapes of the histograms at higher deposit levels separate the 90 percentile values by 4 mg (36 mg versus 40 mg, for North America and Europe, respectively).

### Engine Oils in Asia

Engine oils collected in Asia (India, China, and the Pacific Rim countries) were also studied as to turbocharger deposit-forming tendencies using the TEOST 33C bench test. Results are shown in Figure 11.

The shapes of the Asian histograms were found to be generally different from those of Europe and North America suggesting a different approach to additive and base stock formulation

One potential source of the relatively low simulated turbocharger deposit level shown by the collected Asian oils was considered. Perhaps some of the engine oil additive levels were lower which, as shown earlier in this paper, would tend to reduce deposit levels.

Accordingly, the IOM Engine Oil Database was again used to determine the additive levels shown by the elemental analyses of the Asian engine oils. It was found, however, that although the proportion of low additive-level oils was higher than in European and North American engine oils, the percentage of such oils was only about 1% of the total Asian oils collected. This level would not have had strong influence on the histogram peaks at low deposit levels shown in Figure 11. Thus, much of Asian engine oils fell into the low turbocharger deposit range with 50 percentile less than 14 mg rod deposit in the TEOST 33C turbocharger deposit emulsion bench test.

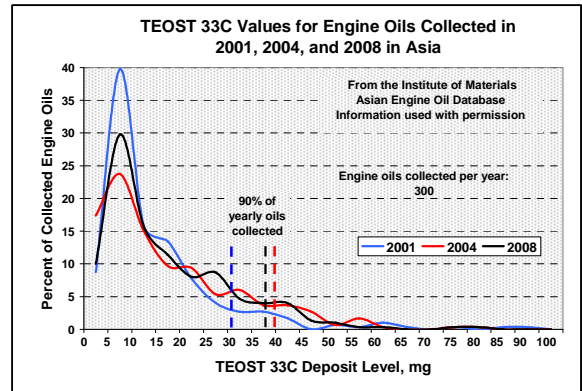


Fig. 11 – Histograms of bench test simulation of turbocharger deposits of Asian engine oils.

### General Comparison of Turbocharger Deposit-Forming Tendencies

Table 1 and Figure 12 summarize the histogram values shown in the previous Figures 8, 9, and 11 at 50, 75, and 90 percentile levels regarding the deposit-forming tendencies of the engine oils in the three world areas in which the oils were collected by IOM.

It is evident that the turbocharger deposit levels simulated by the TEOST 33C have varied considerably – usually increasing – over the last near-decade.

Table 1 - Comparison of Deposit Levels				
World Area	Year	Percentile of Oils Collected		
		50	75	90
Milligrams Deposit in Bench Test				
Asia	2001	<10.5	<19.0	<30.8
Europe		<12.1	<21.9	<31.0
N. America		<23.5	<30.7	<40.5
Asia	2004	<12.9	<24.9	<39.6
Europe		<16.2	<28.3	<40.0
N. America		<22.5	<30.8	<43.2
Asia	2008	<13.2	<25.1	<37.1
Europe		<19.5	<28.6	<39.4
N. America		<19.3	<25.6	<35.0

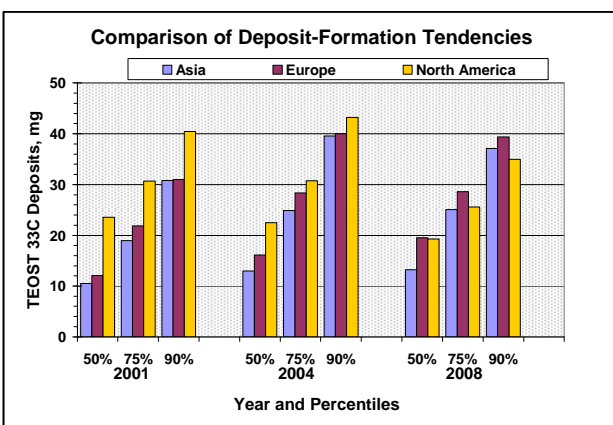


Fig. 12 – Comparison of collected histograms of bench test simulation of turbocharger deposits.



## Discussion

### General Observations and Considerations Regarding Turbocharger Deposits

Formation of deposits in a turbocharger is attributed to

1. frequency of turbocharger use under conditions in which the turbocharger shaft is brought to, and maintained at, high operating temperatures for a considerable length of time, and immediate engine shut-off after each use of the vehicle,
2. additive content and base stock choice in formulating the engine oil,
3. rate at which anti-oxidation additives are exhausted by exposure in the turbocharger and
4. frequency of oil change,

as well as on other factors such as turbocharger design, its location in the engine compartment, and, to some degree, the materials and mass used in its construction.

**Primary Determinant of Turbocharger Deposits** – The primary determinant of whether, and to what degree, turbocharger deposits will occur with a given engine oil formulation is the frequency and duration of high turbocharger turbine shaft temperatures followed by immediate cessation of engine oil flow through the turbocharger bearings after each such operation. This is considered the basic reason why considerable differences in driving patterns in various countries produce reportedly different experiences in the occurrence of coking deposition.

**Effects of Driving Patterns and Traffic Congestion** – It is well known that the influence of engine oil circulating through the turbocharger bearings from the considerably cooler engine environment tends to mitigate deposit-forming tendencies of the oil during operation under more severe driving conditions – particularly when followed by subsequently less demanding operation.

This observation is important in countries such as Japan, India and others that have relatively high vehicular densities on virtually all major streets and roads. Consequently, it is difficult to repeatedly, or even occasionally, generate the high turbocharger shaft temperatures that, when followed by immediate engine shut-down, would create coking conditions in the turbocharger.

As a consequence, such driving and traffic influences can somewhat ameliorate the need to formulate engine oils to resist turbocharger deposits (depending on turbocharger design, placement in the engine compartment, etc.). Under these circumstances, additives that may be more susceptible to forming turbocharger deposits at high, sustained, turbine shaft temperatures can be considered in formulations for these more traffic-congested areas of the world which generate considerably lower and variable turbocharger turbine shaft temperatures.

**Deposit-Prone Additive Usage** – The aforementioned positive and negative influence of additives on deposit formation is made evident by the TEOST 33C test. As part of their previously mentioned paper, Yoshida and Naitoh [5] used this test to study one engine oil additive chemistry which was said to improve engine efficiency but was also indicated to be prone to turbocharger deposit formation by the TEOST bench test. That is, at additive concentrations above 500 PPM it would not meet the TEOST 33C maximum limit set for the new engine oil standard ILSAC GF-5. Their study was particularly directed at studying the deposit formation mechanism(s) generated in this bench test.

In their work, Yoshida and Naitoh showed that considerably lower temperatures in the TEOST 33C test (< 440 °C) would allow the particular chemistry to pass the GF-5 specification. Their conclusion was that the metal component of the additive acted as a decomposition catalyst at 480 °C and induced carbonaceous deposit formation.

For this reason, operating conditions in countries with high vehicular densities such as Japan or India, (or in congested cities all over the world) are not as likely to stress the engine oil since it is in contact with a lower temperature turbocharger turbine shaft in comparison to other countries or areas such as the United States. The latter have roads and traffic conditions more likely to provide opportunities for developing high temperature turbine shaft conditions.

Of course, with present-day distribution of certain designs of turbocharged automotive vehicles and certain formulations of engine oils around the world, there is greater reason to be attentive to proper engine oil formulation.

Some interesting analyses and comparisons are shown in the next portion of this paper.

### Additive and Base Oil Susceptibility to Turbocharger Deposit Formation

**North American Engine Oils in 2008** – In comparison to deposit-creating additives, the actual behavior of modern engine oil formulations is shown for North America in 2008 in Figure 13.

It is evident that 75% of North American engine oils in 2008 were below 26 mg deposit in the TEOST 33C turbocharger simulation test as shown in Figure 13. Most of these were formulated to meet specification levels for ILSAC GF-4 and API SM. This 26 mg deposit level has been identified with acceptably low deposits in the turbocharger.

**TEOST 33C Influence in GF-2,-3,-4** – It should be noted that the TEOST 33C test was part of the ILSAC GF-2 specification thus providing formulation experience for ILSAC GF-3 and GF-4 specifications in which it was not included.

**Re-Insertion of TEOST 33C in GF-5** – Development and use of newer additives, base oils of greater oxidation resistance, and growing turbocharger use has led to re-introduction of the TEOST 33C test in ILSAC Specification GF-5 at a maximum deposit level of 30 mg. This deposit level includes over 80% of the oils picked up from the North American market by the Institute of Materials for their engine oil database in 2008 as shown in Figure 13. This data indicates that the present and forthcoming level of turbocharger oxidation control should meet turbocharger needs in an area of the world in which long, steady state, driving is often encountered.

**Comparison of Engine Oils from Europe, Asia, Japan, and North America** – As a measure of present engine oil formulation practices, it was thought to be of interest to

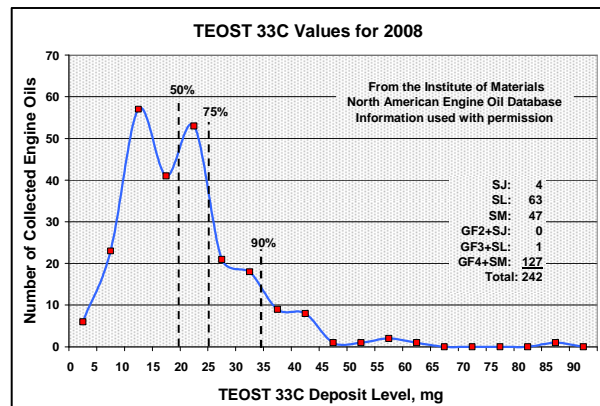
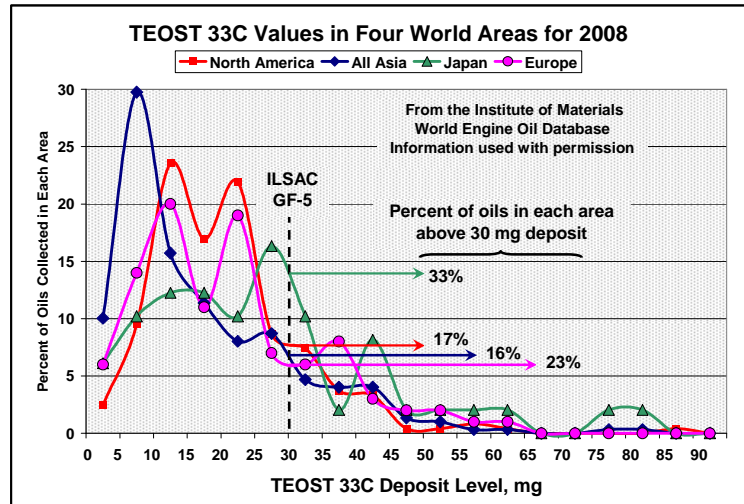


Fig. 13 – Recent histogram of TEOST turbocharger deposits simulation of oils collected in North America in 2008.

compare the turbocharger deposit propensity of engine oils produced and marketed in 2008. This is shown in Figure 14.

Fig. 14 – Comparison of the histograms of engine oils picked up from the market in four areas of the world.



It is evident that there are major differences between some of the areas of the world in terms of concern and/or preparedness for the growing turbocharger presence. The vertical dashed line shows the present maximum of TEOST 33C turbocharger deposit-simulation test of 30 mg on both the Depositor Rod and filter. The horizontal color-matched arrows and percentile values show the percent of engine oils in each area that exceeded the 30 mg maximum limit of ILSAC GF-5. This percentage of engine oils exceeding a deposit of 30 mg ranges from 16 % for all Asia to 33 % for Japan (in which there is greater use of the additive and its deposition mechanism studied by Yoshida and Naitoh [5] mentioned earlier).

**Comparison of Turbocharger and Engine Deposits** – It was thought to be interesting to present a comparison of the relationship between turbocharger deposits and engine deposits simulated respectively by TEOST 33C and TEOST MHT bench tests [7]. This is shown in Figure 15.

Turbocharger-simulated deposit values from the TEOST 33C bench test are plotted on the X-axis against engine ring belt simulated deposits using the TEOST MHT bench test for the same oils all carrying the ILSAC designation GF-4.

The result is that there is essentially no correlation between turbocharger and engine simulating deposit results as shown by a Coefficient of Determination ( $R^2$ ) value of 0.01. Although the correlation between the two deposit values was expected to be relatively low, the value actually obtained was surprising.

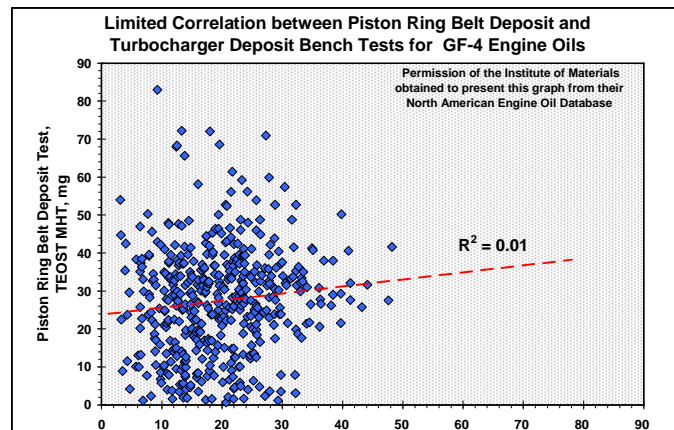


Fig.15 – Degree of correlation of turbocharger deposit simulation and engine ring belt deposit simulation.

## Conclusions

This paper has had several objectives:

1. To present the background and development of the turbocharger deposit-simulating bench test, TEOST 33C.
2. To present the present and past status of turbocharger compatibility of engine oils.
3. To bring to the attention of those interested, the direction of engine oil formulation needed to meet the growing use of turbochargers.

In today's society and, more broadly, today's civilization, the private use of the automobile is a highly visible and often costly way to meet the demands of contemporary lifestyles. As such, it is important for that technical portion of the world concerned with the formulation and application of engine lubricants to apply the skills needed to sustain the automotive mechanism and enhance its service both in longevity and performance satisfaction.

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