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# Change of High-Shear-Rate Viscosity of Engine Oils During Use: A Review

**ABSTRACT:** It has long been known that the kinematic viscosities of multigrade engine oils change with use, the typical pattern being an initial decrease followed by a gradual increase. Recent work has shown that the patterns of change of the high-temperature, high-shear (HTHS) viscosity are different than those of the kinematic viscosity. These results, coupled with recent bearing oil film thickness results, suggest that kinematic viscosity changes are less significant in the operation of the bearings of engines than has been assumed. The pattern of HTHS viscosity change has been found to depend on both viscosity index (VI) improver type and engine test. Oil-thickening effects tend to be more prominent in the HTHS viscosity patterns than in the kinematic viscosity patterns.

**KEY WORDS:** engine oils, polymers, shear stability, shearing, VI improvers, viscometer, viscosity

Ever since the engine oil industry started using polymeric materials, called viscosity index (VI) improvers, to improve the viscosity–temperature characteristics of mineral oils, it has been known that these materials lose thickening capabilities in service as a result of mechanical shearing of the polymer molecules. Oils also lose viscosity because of fuel dilution, but this is primarily a function of the condition of the engine and is not oil-related. Oils used in engines not only tend to lose viscosity because of polymer shearing, but they also tend to thicken as a result of the build-up of combustion products in the oil, oxidation, and evaporation of the lighter components of the base oils. Because these two tendencies oppose each other, the viscosity change in service is the resultant balance between them.

The change of oil viscosity with use in an engine has been a long-time concern of engine manufacturers around the world. This concern is demonstrated by military "stay-in-grade" specification in the United States, as well as automotive industry "shear stability limits" using laboratory test methods in Europe (CEC L-78-A-79: "Shear Stability of Lubricating Oils Containing Polymers Using an Injector Rig"). Recently, one U.S. passenger car manufacturer has also added "shear stability limits" as determined by the ASTM Test for Shear Stability of Polymer-Containing Fluids Using a Diesel Injector Nozzle (D 3945) to its own engine oil specifications.

The viscosity changes occurring in service are affected by many variables. The tendency of oils to lose viscosity because of shearing depends on the type, molecular weight, and concentration of the VI improver. This tendency increases as the concentration and the

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molecular weight of the polymer increase, and as the viscosity of the oil increases. The tendency to shear also depends on the design and the operating conditions of the engine. The tendency of oils to thicken depends on the dispersant-inhibitor (DI) package in the oil and the operating conditions of the engine; high operating temperatures tend to promote thickening. Also, the thickening tendency depends on the viscosity of the oil; low-viscosity oils are more subject to evaporative thickening than high-viscosity oils because the former contain more of the light components. To make meaningful comparisons of the viscosity changes among various VI improvers in engine service, the test oils should be blended to the same SAE grade, because this way, the concentrations will be those at which each VI improver will typically be used. Additionally, the test oils should contain the same DI package.

The viscosity changes of oils in service have traditionally been determined on the basis of kinematic viscosities as measured by the ASTM Test for Kinematic Viscosity of Transparent and Opaque Liquids (D 445) at 100°C, which has a shear rate on the order of 100 reciprocal seconds. In recent years, it has become increasingly evident that engines, particularly in the bearing areas, respond to the viscosity of oils as measured at shear rate and temperature conditions that are characteristic of those that occur in the bearings [1,2]. Other work [3,4] has suggested that engine operation may also respond to other rheological characteristics of the oils, but there are no agreed upon techniques for measuring such characteristics. At this time, the industry has tentatively settled on a temperature of 150°C and a shear rate of 1 million reciprocal seconds as being representative conditions for measuring viscosities for purposes of correlating with bearing oil film thicknesses. For convenience throughout this paper, the viscosity as measured at 150°C and 1 million reciprocal seconds will be referred to as the high-temperature, high-shear (HTHS) viscosity, whereas the viscosity as measured by the normal-temperature, low-shear kinematic viscosity test will be referred to as the NTLS viscosity.

It will be helpful to review the definition of various viscosity losses that occur with VI-improved oils due to the presence of the VI improver. In 1973, Gyer [5] published a figure similar to Fig. 1, showing the viscosity as a function of shear rate for a hypothetical oil before and after being sheared in the absence of oxidative thickening. The change from Point A to Point C is the NTLS permanent viscosity loss. The change from Point A to B is called the temporary viscosity loss; it reflects the reversible elongation and alignment of the polymer molecules that occur in a shear field. The loss from Point B to Point D is the viscosity loss at high-shear rate. Gyer [5] noted that the high-shear-rate viscosity losses were less than the low-shear-rate losses and stated that "... at shear rates typical of machine elements such as journal bearings, polymer viscosity loss due to mechanical degradation is not as serious as low shear rate data indicate."

Figure 2 shows hypothetical curves for the new- and used-oil viscosities at both 100 and 150°C. The loss from Point E to Point G is viscosity loss at high temperature and low shear rate. The loss from Point F to Point H is the HTHS viscosity loss.

In most types of engine service, oil thickening overcomes the shear degradation and the viscosity eventually increases over the initial value, so it is more appropriate to refer to "viscosity changes" than to "viscosity losses." There is a great deal of literature available about the changes in the NTLS viscosity in engine service. This paper is a review of the sparse literature on the changes in the HTHS viscosities and the relationship between the HTHS viscosity changes and the NTLS viscosity changes. It also includes new data from our own laboratory. Specifically, it will address the following questions:

  1. What are the relative magnitudes of the HTHS and NTLS viscosity changes?
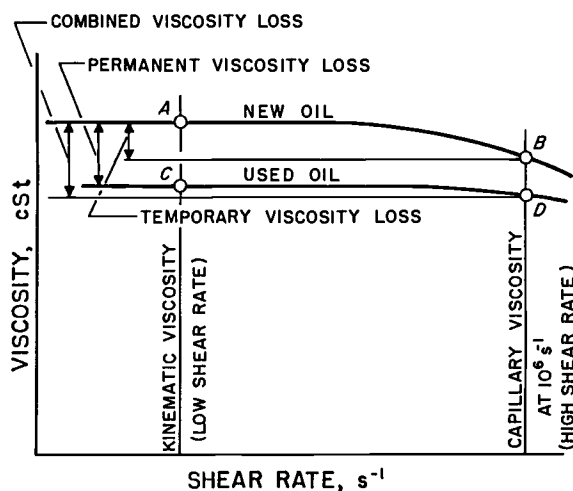  2. How do the viscosity changes differ with engine test?

FIG. 1—*Definitions of viscosity losses at a single temperature.*

3. How do the changes depend on VI improver type and molecular weight?
4. What are the relative effects of thickening on the two viscosity changes?

**Reviews**

Alexander and Rein [6] reported on the relationship between the various viscosity losses in the Fuel Injector Shear Stability Test, which is now Procedure B of ASTM D 3945. In this work, they measured the NTLS and HTHS viscosities of 43 fully compounded SAE 10W-30 and 10W-40 engine oils before and after shearing. Figure 3 shows their data plotted as the HTHS viscosity loss versus the NTLS viscosity loss. As can be seen, the HTHS losses were generally less than half of the NTLS losses. The work included several types of
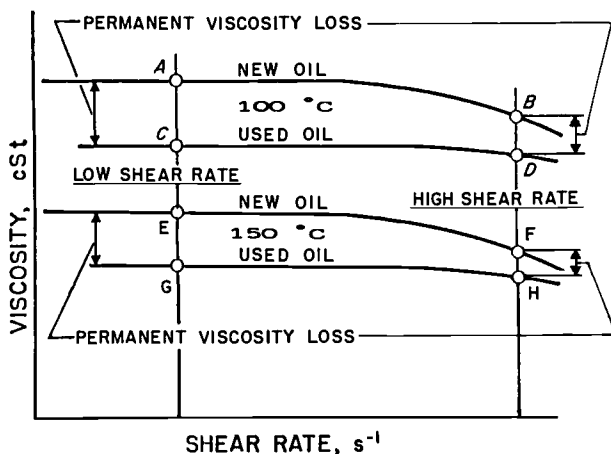


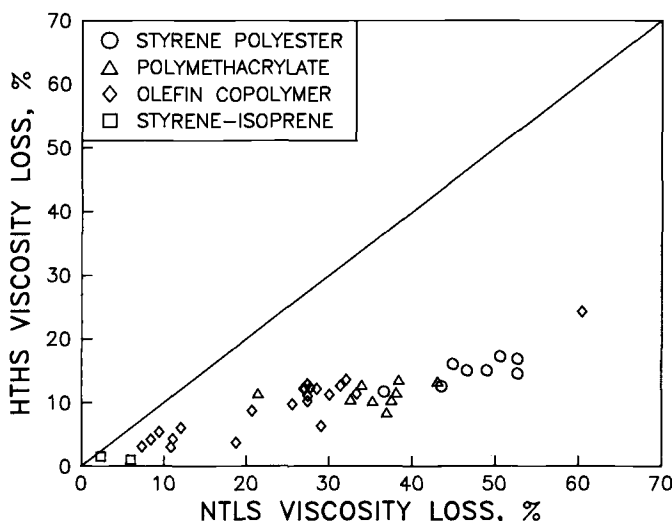FIG. 2—*Definitions of viscosity losses at two temperatures.*

FIG. 3—*Relationship between HTHS and NTLS viscosity losses in the ASTM D 3945 (Procedure B) shear stability test.*

VI improvers (as indicated in the figure legend). Note that each VI improver has its own characteristic viscosity loss range.

Turning now to engine tests, Spooren et al. [7] compared the shear stability of four 20W-50 oils, each containing the same SE quality DI package, in several engine tests and in the DIN 51382 shear stability test. The latter test was the basis for the CEC L-14 test and Procedure A of the ASTM D 3945 test. The viscosity changes, expressed as a percentage of the new oil viscosity, in a 12-h version of the Cortina High Temperature Test (CHTT) and in the CEC L-14 shear stability tests are shown in Fig. 4. The new-oil and used-oil viscosities are shown in Table 1. The CHTT test was a 12-h version of what is normally a 100-h test; the shortened duration was chosen because the viscosity of most oils has reached the minimum value by that time and has begun to increase. As can be seen in Fig. 4, the HTHS viscosity change of all four oils was less than the NTLS viscosity change. For the olefin copolymer (OCP) and the hydrogenated styrene isoprene (HSI) oils, the HTHS viscosity increased over that of the new-oil viscosity, indicating that thickening had overwhelmed the viscosity loss caused by polymer degradation. Also, it can be seen that the NTLS and HTHS viscosity losses from the Co-ordinating European Council (CEC) L-14 test were appreciably greater than those in the engine, showing that the oils were susceptible to large viscosity losses in this rather severe shearing environment.

However, comparing the NTLS and HTHS viscosity changes does not tell the whole story; the HTHS viscosity itself is important. As indicated in Fig. 4, the HTHS viscosity of the HSI oil after the test was appreciably higher than that at the beginning of the test. However, Table 1 shows that the HTHS viscosities of this oil at the end of the test were the lowest of all the oils. The viscosities of this oil were lowest because the thickening power of the HSI VI improver decreases at high temperatures.

Considering only the other three oils, this work showed that the thickening in this test had a relatively larger effect on the HTHS viscosity change than on the NTLS viscosity. The HTHS viscosities of the three oils changed very little, whereas the NTLS viscosities of all three oils decreased appreciably.
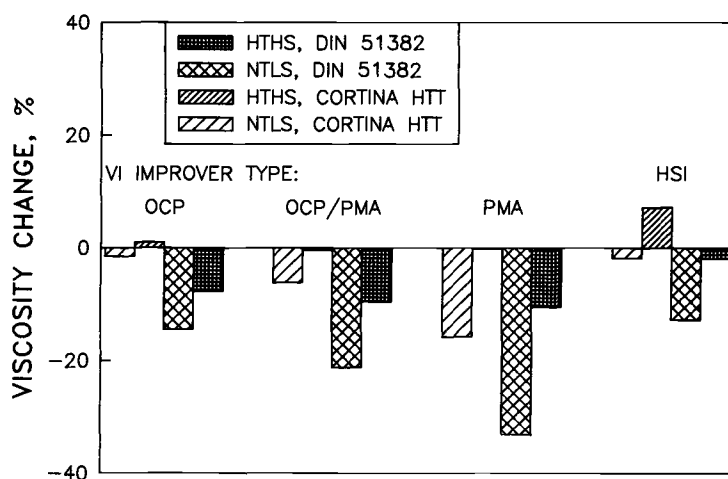
FIG. 4—*HTHS and NTLS viscosity changes in the Cortina High Temperature Test and the CEC L-14 shear stability test.*

Rein et al. [8] reported both the HTHS and NTLS viscosity losses in extended duration CRC L-38 tests, in V-6 laboratory engine tests, and in automobile road tests. The viscosities of the oils were measured as the tests progressed, so the effects of test duration could be followed. Four SAE 5W-30 oils were used throughout these tests. Each contained a different VI improver, but all contained the same SF/CC quality commercial DI package. The oils were blended to the same NTLS viscosity and Cold Cranking Simulator viscosity levels.

The new-oil NTLS and HTHS viscosities are shown in Table 2. The viscosity changes have been plotted in the form of the retained viscosities, both the NTLS and the HTHS, versus the test duration in Figs. 5 through 7 for the L-38 tests, the laboratory engine tests, and the road tests, respectively. The retained viscosity is the viscosity at a particular time

TABLE 1—*New-oil and used-oil viscosities in Cortina High-Temperature Test and DIN 51382 test.*

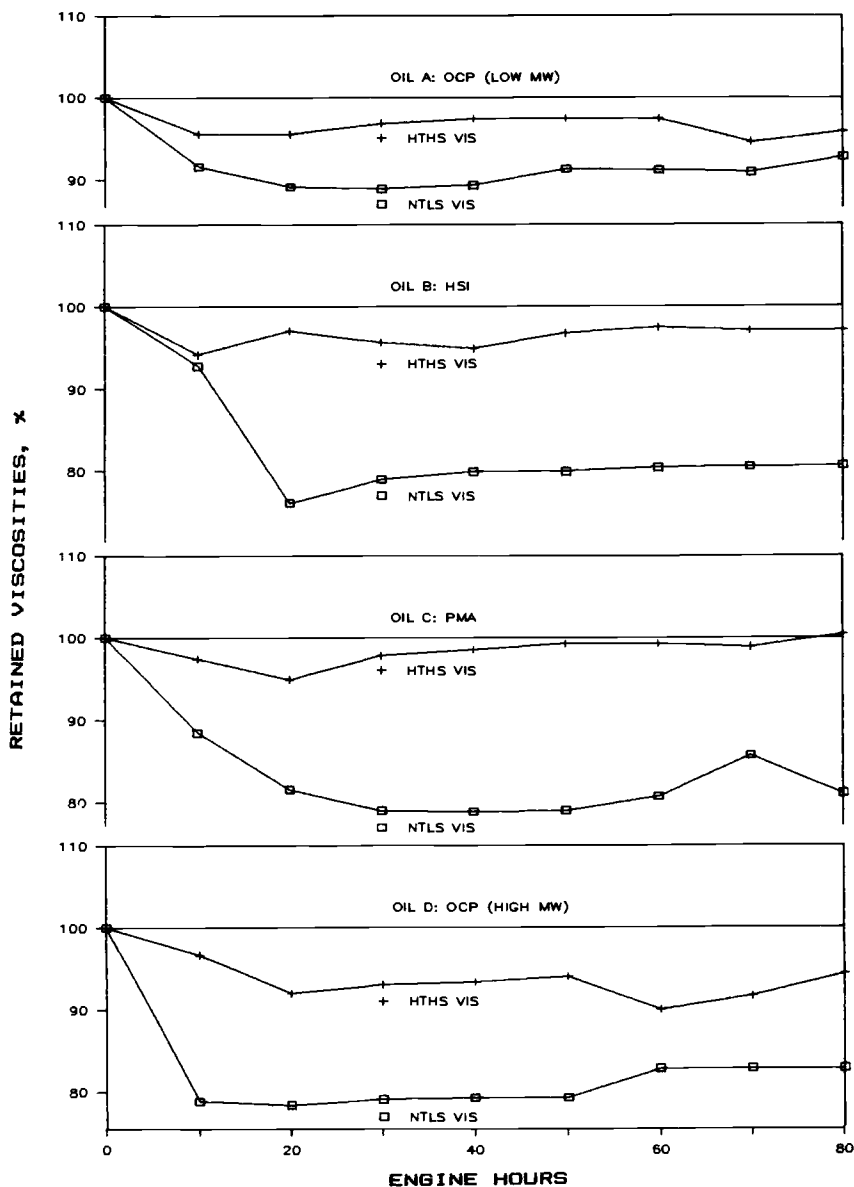| | New-Oil Viscosities | | Used-Oil Viscosities | |
|---|---|---|---|---|
| | NTLS Vis., cSt[a] | HTHS Vis., cSt | NTLS Vis., cSt | HTHS Vis., cSt |
| | CORTINA HIGH TEMPERATURE TEST | | | |
| OCP OIL | 21.73 | 7.05 | 21.40 | 7.12 |
| OCP/PMA OIL | 21.80 | 6.75 | 20.44 | 6.72 |
| PMA OIL | 20.33 | 5.81 | 17.12 | 5.80 |
| HSI OIL | 20.02 | 5.30 | 19.65 | 5.68 |
| | DIN 51382 TEST | | | |
| OCP OIL | 21.73 | 7.05 | 18.58 | 6.51 |
| OCP/PMA OIL | 21.80 | 6.75 | 17.17 | 6.10 |
| PMA OIL | 20.33 | 5.81 | 13.60 | 5.20 |
| HSI OIL | 20.02 | 5.30 | 17.45 | 5.20 |

[a] 1 cSt = 0.000 001 $m^2$/s.

FIG. 5—*HTHS and NTLS retained viscosities of SAE 5W-30 oils in the L-38 test.*

expressed as a percentage of the new-oil viscosity. This normalizing technique allows a ready comparison between the NTLS and HTHS viscosity changes.

As can be seen from these three figures, the HTHS viscosities of the used engine oils decreased, on a percentage basis, much less than the NTLS viscosities in all of the tests. The differences between the losses depended on the VI improver and on the particular engine test. In general, the HTHS viscosity decreases were less than half of those of the
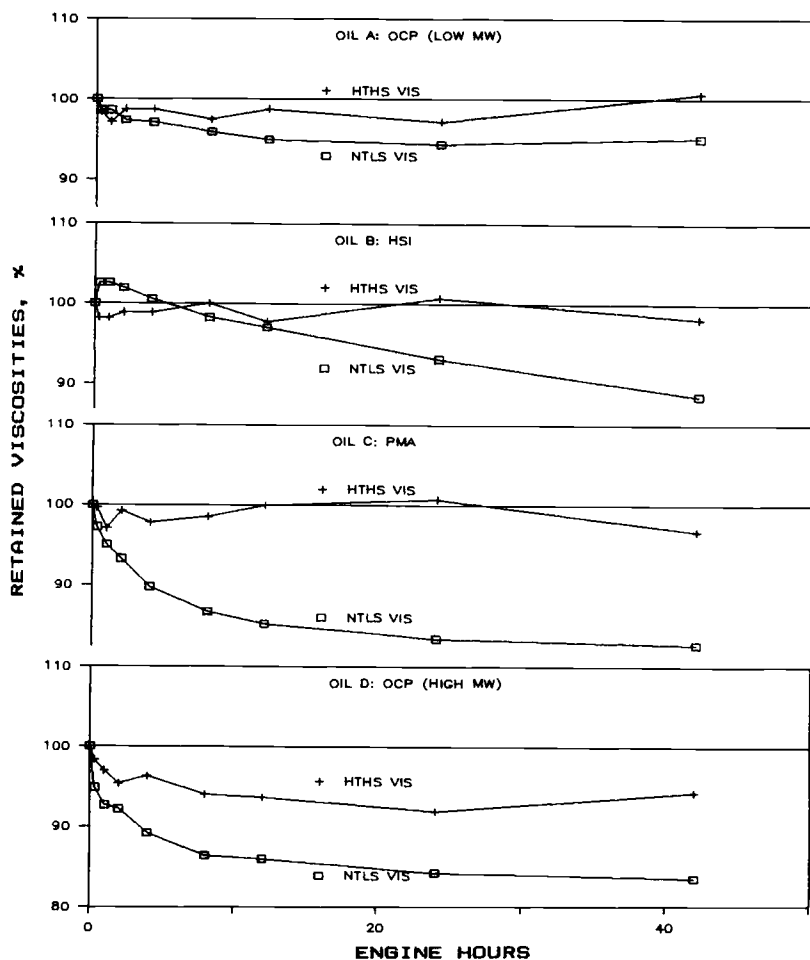
FIG. 6—*HTHS and NTLS retained viscosities of SAE 5W-30 oils in a V-6 engine test.*

NTLS viscosity losses. In all three engine tests, the HTHS viscosities of Oil C decreased very little, if at all, whereas the NTLS decreased substantially.

Figures 5, 6, and 7 are presented in order of decreasing shear severity, based on the minimum NTLS viscosities during the course of the tests. The ratios of the HTHS viscosity change to the NTLS viscosity change do not appear to vary significantly with the shear severity of the engine.

In general, the thickening of the oils in these engine tests tended to overcome the HTHS shear losses more readily than the NTLS losses. The times for the HTHS viscosity to reach its minimum value were shorter than the corresponding times for the NTLS viscosity. And in those tests in which significant thickening occurred, the times for the HTHS viscosity to equal the new-oil viscosity were generally shorter than the corresponding times for the NTLS viscosity.

Because the oils in this work contained the same DI package, the shear stability of the four VI improvers by each viscosity measure can be compared. These comparisons were done in terms of the minimum viscosity at any time/mileage throughout the test. Because
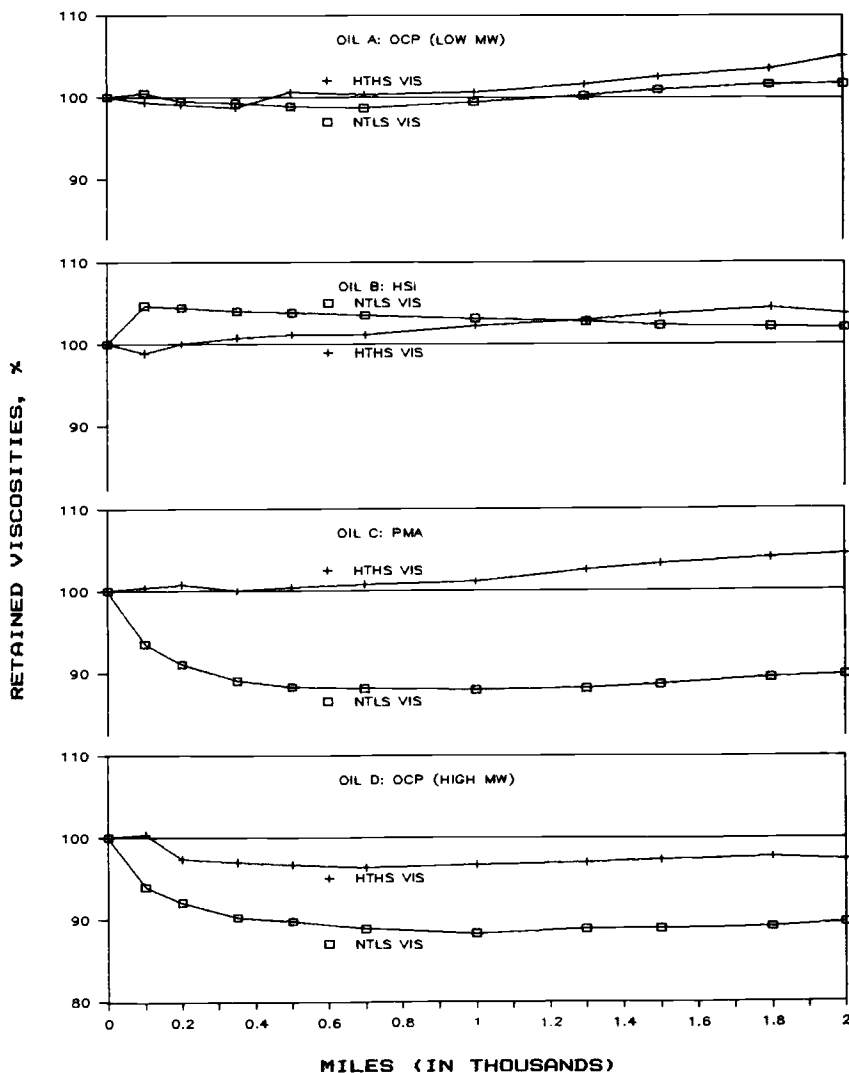
FIG. 7—*HTHS and NTLS retained viscosities of SAE 5W-30 oils in an automobile road test.*

some of the low viscosity points appeared to be untypical, only those minimum values that appeared to be typical were used. As can be seen on Table 2, the HTHS minimum viscosity of Oil A was the highest in all three tests, and the HTHS viscosity of Oil D was next to the highest. The differences between the minimum viscosities of Oils B and C were negligible. Note that the NTLS minimum viscosity of Oil B was either the highest or next to the highest in the V-6 engine and in the road test, but the HTHS minimum viscosity was the lowest in those tests. The difference between Oils A and D, both of the OCP type, reflects the relative molecular weights of the VI improvers.

One anomaly in this work was the initial increase of the NTLS viscosity of Oil B in the V-6 engine and the road test. It is possible that the VI improver was not completely dis-

TABLE 2—*New-oil viscosities and minimum viscosities during use in engines.*

| | New-Oil Viscosities | | Minimum Viscosities | |
|---|---|---|---|---|
| | NTLS Vis., cSt[a] | HTHS Vis., cP[b] | NTLS Vis., cSt | HTHS Vis., cP |
| REIN ET AL. OILS: SAE 5W-30 | | | | |
| 80-H L-38 Test | | | | |
| Oil A | 10.58 | 3.14 | 9.40 | 3.00 |
| Oil B | 10.51 | 2.72 | 8.30 | 2.58 |
| Oil C | 10.48 | 2.75 | 8.27 | 2.61 |
| Oil D | 10.67 | 3.00 | 8.37 | 2.75 |
| V-6 Engine Test | | | | |
| Oil A | 10.58 | 3.14 | 9.98 | 3.05 |
| Oil B | 10.51 | 2.72 | 9.31 | 2.67 |
| Oil C | 10.48 | 2.75 | 8.66 | 2.67 |
| Oil D | 10.67 | 3.00 | 8.93 | 2.81 |
| Road Test | | | | |
| Oil A | 10.58 | 3.14 | 10.44 | 3.10 |
| Oil B | 10.51 | 2.72 | 10.51 | 2.69 |
| Oil C | 10.48 | 2.75 | 9.21 | 2.75 |
| Oil D | 10.67 | 3.00 | 9.42 | 2.89 |
| ASTM BFT OILS | | | | |
| SAE 5W-30 Oils | | | | |
| BFT-14 | 10.70 | 3.03 | 10.00 | 2.91 |
| BFT-19 | 10.62 | 2.98 | 10.33 | 2.98 |
| BFT-22 | 10.47 | 2.68 | 10.07 | 2.57 |
| BFT-25 | 10.80 | 3.16 | 10.58 | 3.04 |
| SAE 10W-40 Oils | | | | |
| BFT-16 | 14.01 | 3.80 | 11.73 | 3.50 |
| BFT-21 | 14.35 | 3.88 | 13.40 | 3.87 |
| BFT-24 | 14.09 | 3.26 | 13.08 | 3.20 |
| BFT-27 | 13.95 | 3.90 | 13.20 | 3.74 |
| DIESEL ENGINE OILS | | | | |
| SAE 15W-40 | | | | |
| Oil X | 14.20 | 3.97 | 12.67 | 3.63 |
| Oil Y | 14.69 | 4.04 | 14.23 | 3.81 |

[a] 1 cSt = 0.000 001 $m^2$/s.
[b] 1 cP = 0.001 Pa·s.

solved at the start of the test, which caused the viscosity to be untypically low. This effect would not be seen in the HTHS viscosity measurements because the high shear rate of the viscosity test, itself, would tend to dissolve the VI improver.

## New Work

Two recent studies carried out in our laboratory also examined the changes in the HTHS viscosity during use in the V-6 laboratory engine. The first study was done using the ASTM BFT engine oils discussed elsewhere in this symposium. In both studies, the operating procedure consisted of running the six ASTM Phase III conditions [2], which required about 4 h, then operating about 44 h at 2500 r/min (22.4 kW [30 HP] load, bearing-exit temperature at 100°C, coolant-out temperature at 95°C), followed by rerunning the six ASTM

Phase III conditions. The HTHS viscosities of the oils were measured using the Cannon High Shear Viscometer [9].

The VI improvers in these oils are not identified, but it is known that the following pairs of oils each contain the same VI improver: BFT-14 and BFT-16, BFT-19 and BFT-21, BFT-22 and BFT-24, BFT-25 and BFT-27. Figures 8 and 9, showing the HTHS and NTLS retained viscosities of the four 5W-30 and four 10W-40 ASTM BFT oils, respectively, have
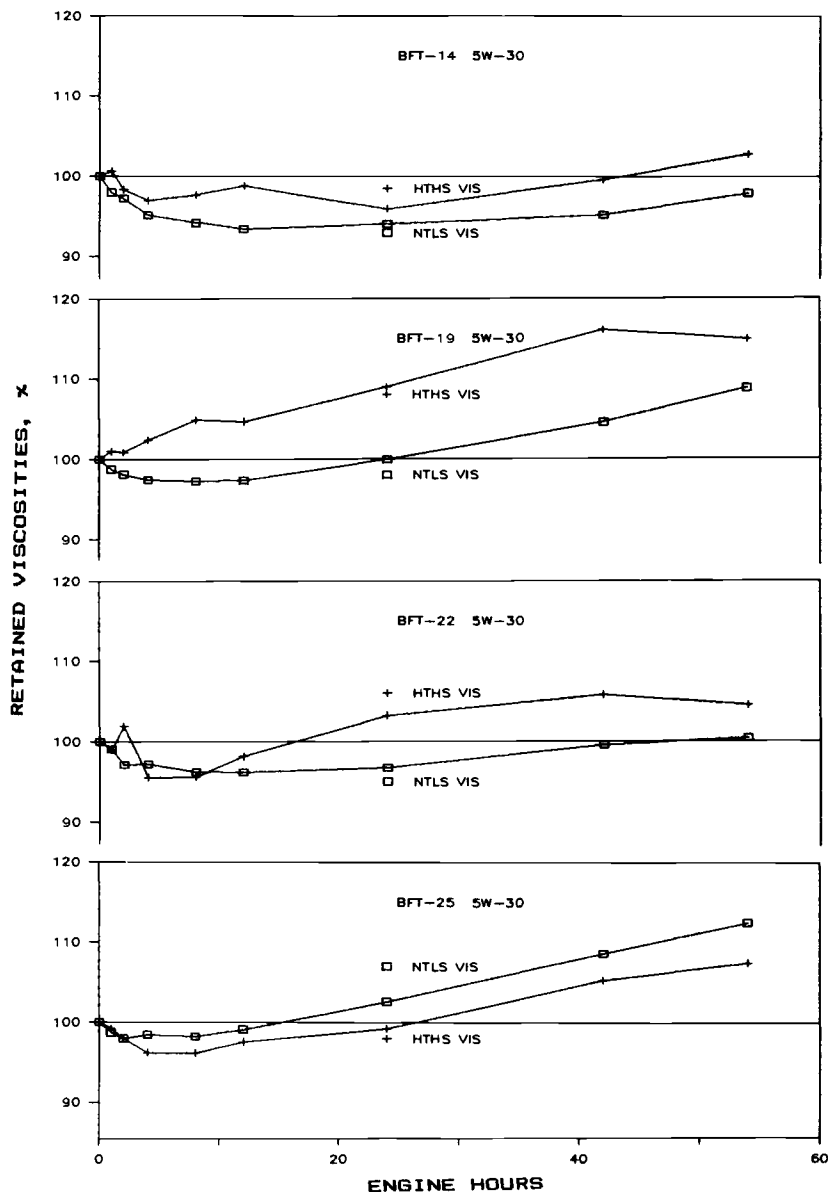


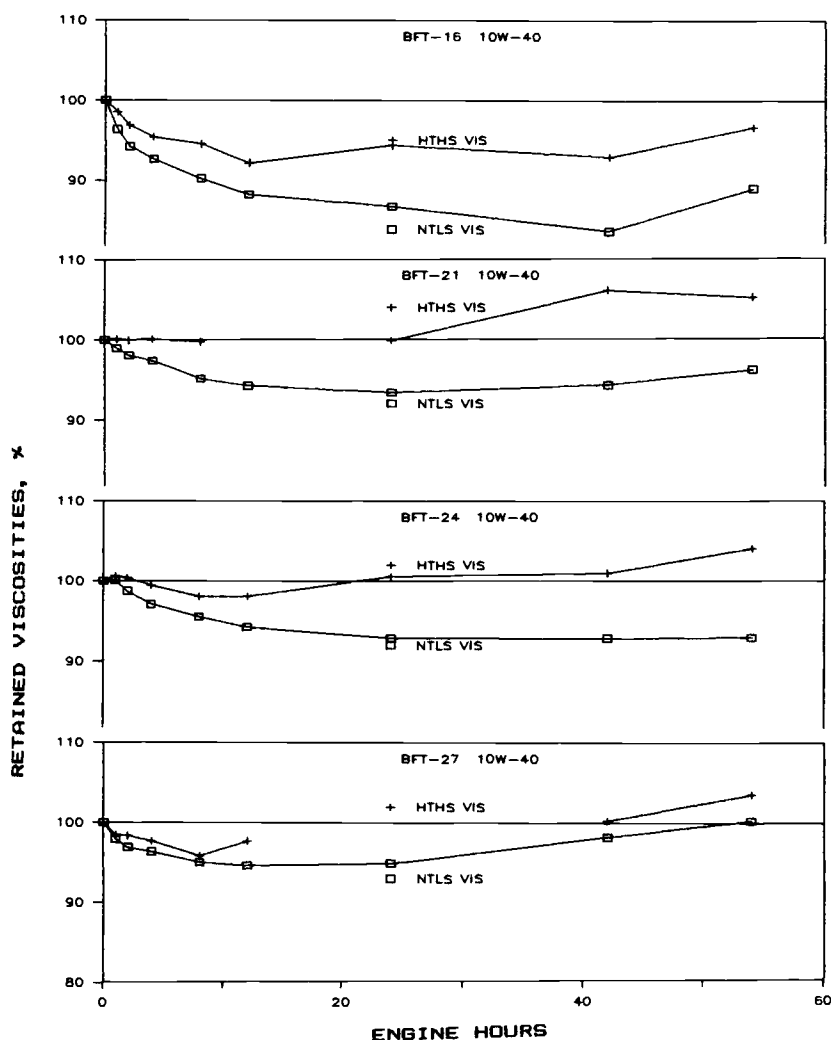FIG. 8—*HTHS and NTLS retained viscosities of ASTM BFT SAE 5W-30 oils in a V-6 engine test.*

FIG. 9—*HTHS and NTLS retained viscosities of ASTM BFT SAE 10W-40 oils in a V-6 engine test.*

the VI improvers in the same relative position. The viscosities of the oils are shown in Table 2. These oils did not contain the same DI packages.

As can be seen in Figs. 8 and 9, the HTHS viscosity decreases were less than the NTLS decreases, with the exception of BFT-25, for which both losses were quite small.

These figures also show that both the HTHS and NTLS viscosity losses of the 10W-40 oils were higher than those of the 5W-30 oils. This is because the concentration of a specific VI improver required to produce a 10W-40 oil is greater than that required to make a 5W-30 oil, and because the severity of the shearing of a device increases with the viscosity of the oil being sheared.

These results also showed that thickening of the oil plays a larger role in the changes of the HTHS viscosity than it does in the NTLS viscosity changes. In Figs. 8 and 9, it can be

seen, again, that the HTHS viscosities tended to reach their minimum values earlier in the test than did the NTLS viscosities. The HTHS viscosities also tended to return to their original values during the course of the test, whereas the NTLS viscosities either did not, or did so much later in the test. Again, the exception was BFT-25.

The second investigation in our laboratory showed that the DI package, and perhaps other variables in the composition of the oil, may be more important than the shear stability of the VI improver in determining the HTHS viscosity changes. Two oils, both commercial CE/SF quality 15W-40 heavy-duty diesel engine oils (DEO), were tested in the laboratory V-6 engine test using the procedure described earlier. As can be seen in Table 2, DEO Y was more viscous than DEO X. The shear stability characteristics of the oils were very similar in the ASTM D 3945 (Procedure A) test, as can be seen in Fig. 10, which suggests that the oils contained the same VI improver at about the same concentration.

In the engine test, both the NTLS and HTHS viscosities of DEO Y decreased slightly at the beginning of the test and then increased rapidly, while both viscosities of DEO X decreased throughout all but the last portion of the test (Fig. 11). The difference between
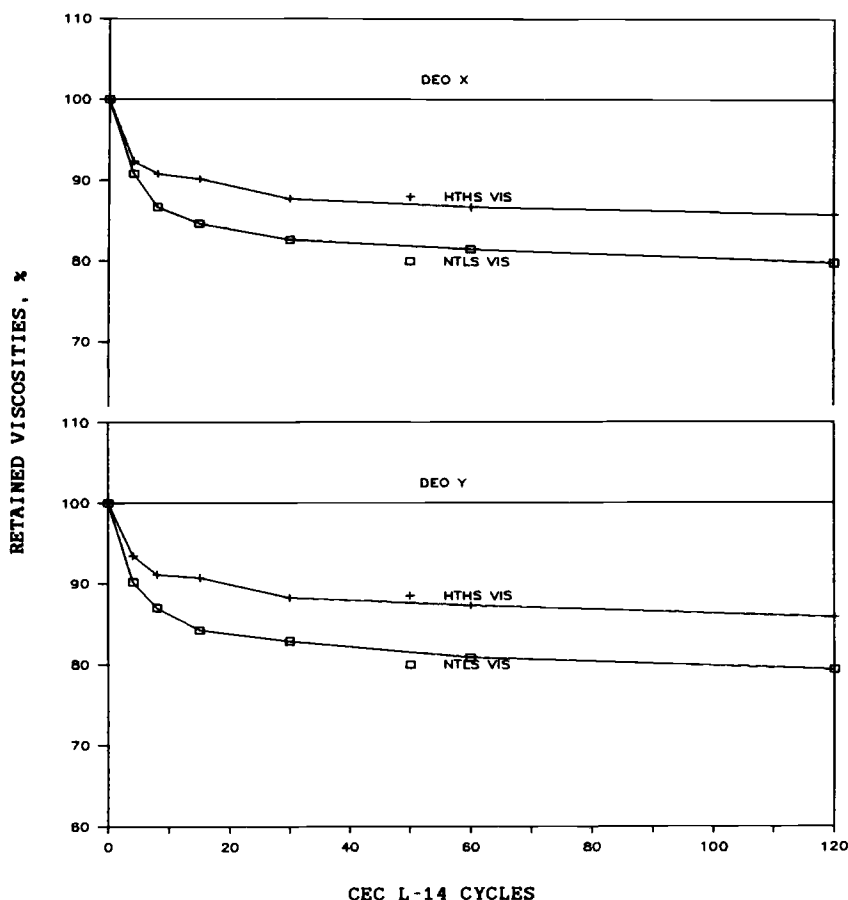


FIG. 10—*HTHS and NTLS retained viscosities of SAE 15W-40 oils in the ASTM D 3945 (Procedure A) shear stability test.*
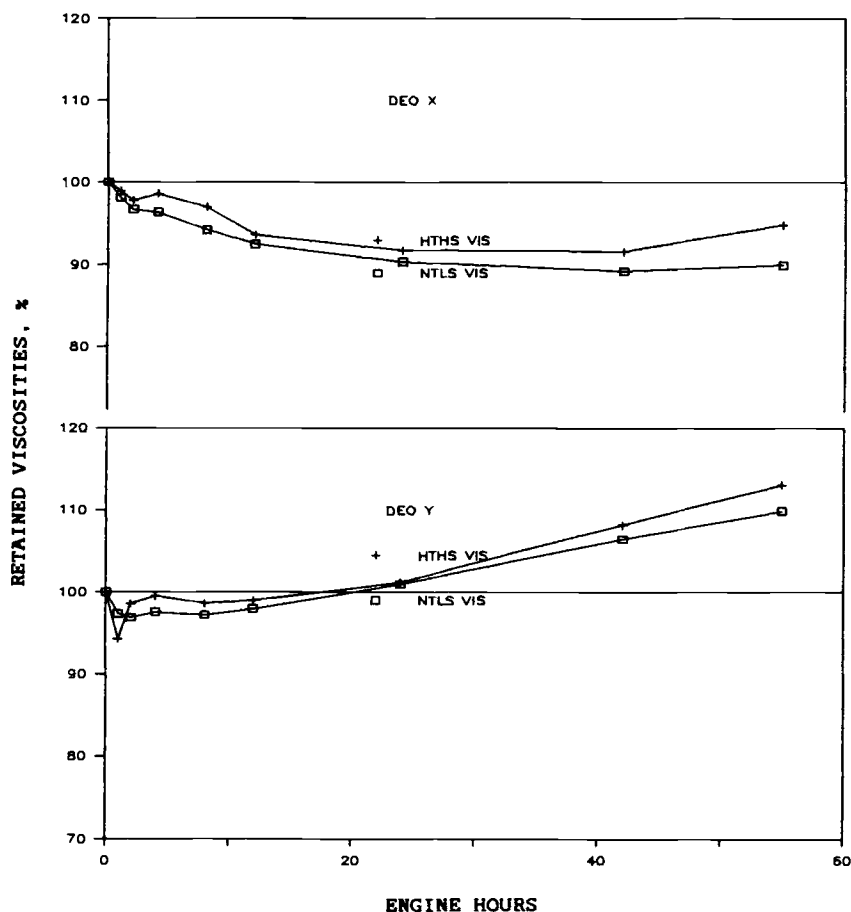
FIG. 11—*HTHS and NTLS retained viscosities of SAE 15W-40 oils in a V-6 engine test.*

the viscosity changes of the two oils was due to a difference in the DI packages, or possibly the base oils, because the VI improvers in the two oils were similar. Note that these oils were unusual in that, for both, the HTHS viscosity changes were very close to the NTLS viscosity changes.

**Summary**

To summarize the available information, HTHS viscosity losses are, in general, appreciably smaller than the NTLS viscosities. The extent of the difference depends strongly on the type of VI improver and the DI package. There was little indication that the difference between the HTHS and the NTLS viscosity changes depends on the type of engine.

Where thickening was a major factor, whether because of the nature of the DI package in the oil or the oxidative severity of the test, the thickening overcame the HTHS viscosity loss sooner in the life of the oil than it did the NTLS viscosity loss. Indeed, oils that contain shear stable VI improvers may undergo only negligible decreases in the HTHS viscosity or the HTHS viscosity may increase throughout the life of the oil.

The results covered in this review speak to one final question: If the SAE J300 Engine Oil Viscosity Classification were to be based on the HTHS viscosity, would shear stability be a concern in the selection of VI improver? To answer this, let us compare the ratio of the observed maximum NTLS viscosity loss to the range of the current SAE 30 grade with the ratio of the maximum HTHS viscosity loss to the range of an assumed future HTHS-based SAE 30 grade. The largest NTLS viscosity loss observed in engines was about 22% while the range of the current SAE 30 grade is 9.3 to 12.5 cSt (9.3 to 12.5 $\mu$m$^2$/s) or about 26%. Thus, the ratio of maximum loss to grade range is 0.85, or in other words, the losses were as large as 85% of the range of the current grade. The largest HTHS viscosity loss was about 10%. If the future HTHS SAE 30 grade limits were 2.8 to 3.5 cP (2.8 to 3.5 mPa·s), then the range is 20%. Thus, the ratio of maximum loss to grade range is 0.5, or, in other words, the losses were only as large as 50% of range of the assumed grade. These numbers indicate that if the viscosity classification were based on HTHS viscosity, then viscosity loss during engine service would be of less concern than it is now, but they do not suggest that the viscosity loss can be ignored.

## Acknowledgments

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