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Problems in Bench Test Prediction of Engine Oil Performance at Low Temperature

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Problems in Bench Test Prediction of Engine Oil Performance at Low Temperature

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ABSTRACT

The author points out the necessity of a reevaluation of the SAE J300 Engine Oil Viscosity Classification System and of the instruments and bench tests developed over the last 30 years to predict low-temperature engine oil performance. Greater ease in starting engines at low temperatures as a consequence of lower friction, electronic timing, and fuel injection has resulted in engines with potentially much higher Critical Starting Viscosities than those which formed the basis for the low-temperature portion of the SAE J300 Classification System. Presenting some of the pertinent low-temperature data available from a well-known engine oil database, the author discusses the consequences of this situation with regard to a number of questions related to the present application of pumpability and startability bench tests, their limitations, and the importance of finding ways to meet the technical challenges. In an effort to encourage dialogue, a suggested replacement for the low-temperature section of the SAE J300 Classification System is proposed which would alter the present system's startability-bias with a gelation-bias reflecting both the improvement in engine startability and the resultant increasing vulnerability of the engine to air-binding phenomena.

FOREWORD

It should be made clear at the beginning of this paper that the author has been closely associated with the origination and development of the Scanning Brookfield Technique and with its later commercial implementation in response to others requesting such equipment. This more recent development has come about as a result of his work in the low-temperature rheology of engine oils for most of his career. In the process, he has formed, expressed, and published his opinions on several facets of this rheological subject as objectively as possible. This paper will be no exception but will contain critiques which could be easily confused with bias on the author's part. While legitimate concerns and critiques are often difficult to accept by those who may have different opinions, with hope, any actual bias or error on the author's part will be corrected by those more knowledgeable on the subject -- and any such objective correction will be received and acknowledged with the author's gratitude.

INTRODUCTION

BACKGROUND AND INTENT OF PAPER -

Since the middle '50s, measurement of the low-temperature rheological properties of lubricants has grown more complex -- particularly for engine oils which must meet increasingly higher user expectations over the wide temperature range in which the automobile is expected to operate. As the relationship between these rheological measurements and the performance of engine oils became clearer, specifications have been written and the engine oil classification system modified to apply such growing knowledge.

As is virtually always the case in the attempt to develop bench tests correlating with field experience, compromises were sometimes necessary. Usually these were in the interests of having tests that, while having significance regarding the engine, were also simple and, particularly, relatively quick to run. Not infrequently, such compromises have been based on misconceptions. Unfortunately, once firmly set in place, such situations are usually only correctable through evident contradiction by Nature.

Today, with numerous important changes in automobile engines and their operation -- electronic timing, lowered friction, fuel injection, low emissions, fast starting, high idling, electronic timing, etc., -- it is time to appraise how successfully both older and newer bench tests developed over the last 40 years can be expected to meet the low-temperature needs of the engines of today and tomorrow. The intent of this paper is to

1. critically appraise the tests designed to predict starting and pumpability of engine oil at low temperatures,

2. anticipate problems in areas now served by any of these bench tests, and

3. form observations and ask questions which, with hope, will not only be helpful in avoiding potential problems, but will suggest avenues of potential success in meeting the present and near-future needs.

BACKGROUND

STARTABILITY -

General Comments - Overall utility of the family car has always been important to the automobile manufacturer and the lubricant formulator. For this reason, improvement of low-temperature startability of the engine has always been high on the work list of those concerned about the automobile and its lubrication.

Very early in the history of the automobile, the perceived need was to develop engine oils of such low viscosity that even the most difficult engine had a reasonable chance of starting -- as long as the oil also had enough viscosity to provide hydrodynamic lubrication to the bearings and cylinder walls in high temperature operation. Technology-driven tension between these two aspects of an engine oil property has occupied the center stage of engine oil viscometrics for decades and has led to many changes in base oils and formulations in the effort to accommodate both aspects.

Beginnings of Bench Tests - The relationship between engine oil viscosity and ease of starting the engine has been recognized as long as the engine itself. Only in the 1950s, however, did it become evident that the viscosity of engine oils, particularly polymer-containing oils, must be measured with suitably high shear stress instruments in order to build a correlation with engine startability[(**1**) a literature review].

After much work went into the development of engine data on selected reference oils and the evaluation of a half dozen proposed viscometers(**1**), the Cold-Cranking Simulator method was adopted by the ASTM as D2602 in 1967(**2**) to determine viscosities of engine oils at 0°F (-17.8°C). (Very recently the general method has been revamped with a multi-temperature method, ASTM D5293(**3**).)

Correction of Perception - Cranking speed has long been thought to be the prime factor in determining startability of spark ignition engines at low temperatures (when sufficient battery energy and a combustible fuel mixture in the cylinders were available). The role of viscosity was (and often still is) viewed as opposing the cranking speed thus making starting more difficult. This conventional wisdom was tested in the early 1960s(**4**) and it was found that with proper fuel and carburetion, the spark-ignition engine can be started at almost any speed if oil viscosity is low enough. Conversely, it was also shown that no cranking speed is sufficient (below 150 RPM) if the viscosity is too high. The critical factor -- ability of the **firing** engine to overcome the viscous traction barrier at very low starter-disengaged, **running** speeds (~200-300 RPM) -- had been hidden behind what seemed to be an obvious relationship between cranking speed and viscosity.

However, at a time when most engines were naturally aspirated and fuel volatility, efficiency of carburetion, cranking speed, and temperature were entwined, this demonstrated direct relationship between startability and viscosity (rather than cranking speed) was subject to sharp discussion regarding the difference between laboratory and field experience(**5**). However, the fuel-injected engines of the recent past and today made the subject of fuel volatility no longer an issue. The prior viscosity-starting-sans-cranking-speed relationship seems confirmed when engines -- relatively free from the constraints of fuel volatility -- and filled with recommended low viscosity SAE grades of engine oil, now demostrate dramatically improved startability.

It is important to mention that in the process of generating this study of the relationship between viscosity and startability at low temperatures, the work actually involved more than one design of engine at the time. However, details of results on only one engine (the one most susceptible to starting problems) were reported in the paper. The unreported portion of the study indicated that two different designs of engines had widely different Critical Starting Viscosities ranging from 3500cP (mPa•s) to well over 10,000cP (mPa•s).

Instruments and Low-Temperature Viscosity Specifications - Once bench tests were in hand(**1**), viscosity limits were based conservatively on the most reluctantly starting engine. For example, a maximum acceptable viscosity of 3500cP (at different temperatures) was set for SAE grades of 5W, 10W, and 15W in SAE J300SEP80 Engine Oil Viscosity Classification.

Consequences of Easier Starting - Today, with fuel-injected engines and microprocessor-controlled timing, startability is much easier and more reliable. Consequently, the aforementioned tension is waning -- but giving way to a new set of problems associated with **easier** starting, namely, the problems of **engine oil pumpability** at the significantly lower temperatures at which modern engines may now be reliably started.

PUMPABILITY

PREDICTIONS, ATTITUDES AND REALITY -

Two papers, one in the late '40s(**6**) and another in the early '60s(**7**), cautioned of potential pumpability problems. The former paper was based on engine response, the latter on a low-temperature rheological study of oils clarifying a previous study(**8**) based on extrapolated viscosities. The latter paper(**7**) predicted two forms of failure - one in which the oil forms an internal structure and the other in which the oil simply becomes too viscous. Both papers noted that having startability without pumpability was an invitation to engine failure.

Engine oil pumpability at low temperatures was considered by many to be a 'non-problem' up until 1980 when hundreds of engines failed in the field. These engines failed under particular and somewhat unusual (although not onerous) cooling conditions in both North America and Europe. Apparently, the effect of such cooling on some of the relatively new SE/SF engine oil formulations with base stocks of the time led to air-binding pumpability failures in engines of several makes.

The greater surprise in the field failures was that by that time a bench pumpability test had just been developed

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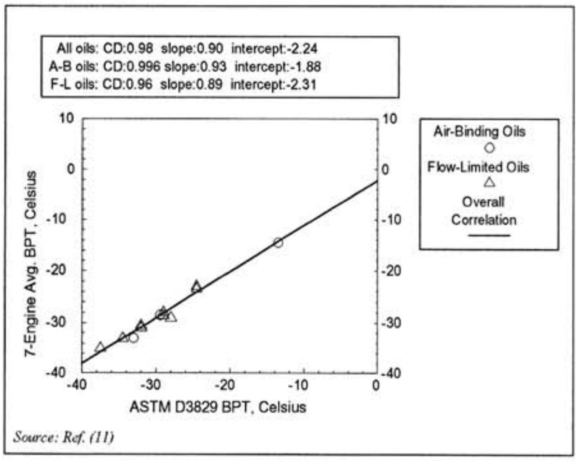
and applied to some of these oils without finding their adverse pumping effects. That pumpability test was ASTM D3829.

ASTM D3829 - THE MINI-ROTARY VISCOMETER -

This test method was based on data from a massive engine pumpability study accomplished under the auspices of the ASTM in the 1970s(**9**). Both engine tests and bench protocol used carefully blended reference oils called the Pumpability Reference Oils or PROs. All of this effort resulted in the development of the Mini-Rotary Viscometer as an acceptable bench test. The method was published as ASTM D3829(**10**), which, as mentioned, was in place at the time of the wide-spread failures to prevent just such engine oil pumpability problems from occurring.

D3829 Correlation with Engine Study - The D3829 bench test had shown excellent correlation with the engine pumpability study. This correlation, shown in **Figure 1**, was made with the Seven-Engine Average borderline pumping temperatures (BPT)(**11**) using a Critical Pumping Viscosity of 30,000cP and a Critical 'Yield' Stress of 105Pa. Flow-limited and air-binding oils -- the two forms of pumpability failure found in the engine studies, were essentially superimposed -- with a slope that is almost unity and an R^2 (Coefficient of Determination) of 0.98 overall. ASTM repeatability and reproducibility were 1.3°C and 3.2°C, respectively.



Source: Ref. (11)

Figure 1 - *Correlation of MRV ASTM D3829 values of BPT with ASTM Seven-Engine-Average BPT using early pumpability reference oils.*

TECHNICAL RECOVERY

NATURE REVEALED -

After the 1980 debacle, it was found by Stambaugh and O'Mara(**12**) just how subtle and devious Nature can be. Consequently, efforts to develop suitable bench tests were redoubled and two proposed bench methods were soon in contention to resolve the problem.

NEW APPROACHES ON THE BENCH -

Data from the first of the new methods was actually presented in a prepared discussion (**13**) of the aforementioned Stambaugh-O'Mara paper. The method used a continuous temperature-viscosity-scanning approach and so was called the Scanning Brookfield Technique (SBT).

The second method was developed in a series of investigative attempts to reapply the MRV(**14,15,16**). Understandably, the presence of a considerable number of MRV instruments in the field as a consequence of the promise of ASTM D3829, led to strong efforts to salvage this instrument as a tool. Some evidence that slower cooling techniques might enhance the usefulness of the MRV was first shown in the aforementioned Stambaugh-O'Mara paper when they exposed an insulation-stripped MRV instrument in their engine cold-room studies and found it gave evidence of gelation with oils previously acceptable in D3829.

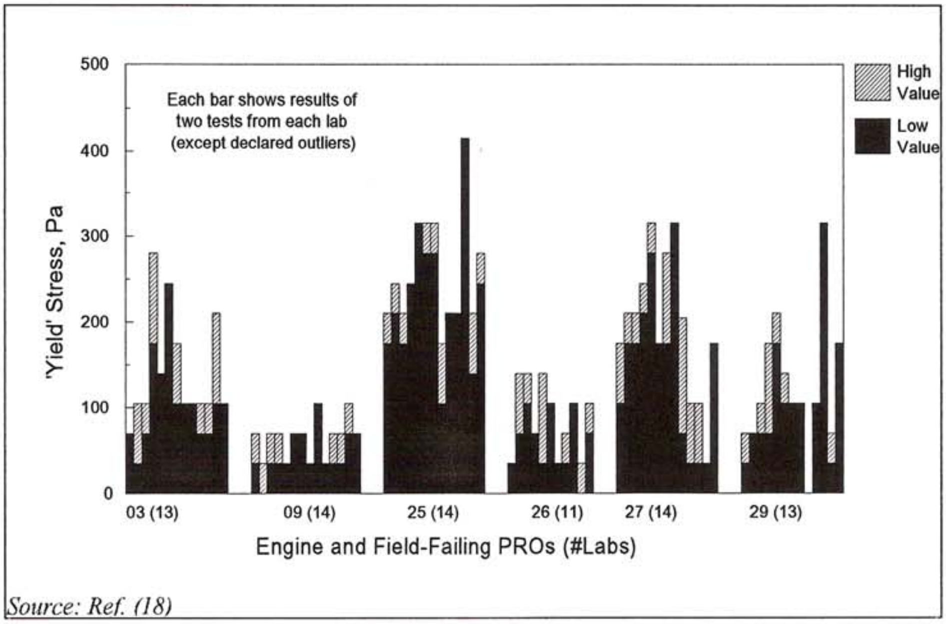
MRV TP-1 AND ASTM D4684 -

After considerable effort(**14,15,16**), a revamped MRV protocol, often referred to as MRV TP-1(**17**) showed the ability to respond to all the field-failing oils.

Basis of Method - The protocol upon which the new MRV method was based was to cool the oil very slowly through a temperature range considered important in developing gelation, then fast-cool to the temperature of test critical to the SAE viscosity grade. Thus, the new protocol would 'collect' any gelation of the oil occurring at some intermediate temperature during slow-cooling and then demonstrate the presence of this 'collected' gelation at the final temperature of analysis. One of the consequences of this choice of protocol was *defacto* elimination of the time-consuming need to find the borderline pumping temperature as in the first D3829 protocol. This saving in running time unfortunately had the negative effect of eliminating the correlation of MRV results with engine borderline pumping temperatures. Further, the inability to cross-correlate using BPT prevented direct reestablishment of the Critical Viscosity for prediction of flow-limited behavior (although indirect correlation with D3829 data was possible).

Undergirding the strategy of 'collecting' gelation over the temperature span of the slow-cooling portion of the test was the tacit assumption that once gelation appeared at some given temperature, it would remain until the test temperature.

New Protocol and Reduction of Test Time - Initial studies focussed on SAE 5W-, 10W-, and 15W-'X' grade oils. To be sure to collect all gelation over the temperature range considered critical, it was found necessary to cool the oils very slowly (≤0.5°C/h) and this introduced the need to find some way to lessen the overall time necessary to run the test: On the basis of the responses of the 10W30 and 10W40 field-failing oils and a few others in wax-formation studies(**16,17**), it was decided that the gelation of concern was a wax-formation phenomenon and was important only over the temperature range down to -20°C. Ultimately, a slow-cool rate of -0.33°C/h was selected with a fast-cool rate of -2.5°C below -20°C. This produced tests ranging from 45 to 51 hours depending on the final test temperature required for the particular SAE grade of the oil.



Source: Ref. (18)

Figure 2 - *Variation of yield stress measurements in ASTM D4684 round-robin.*

Source of 30Pa•s Critical Viscosity - As previously noted, since a Critical Viscosity for the new MRV protocol could not be directly established versus the ASTM engine BPTs on the original PROs, a value of 30,000cP (30Pa•s) was continued unchanged from the D3829 correlation with the ASTM Engine Pumpability Study.

Yield Stress Variation - Effect on Protocol - Unfortunately, during the round-robin using the TP-1 protocol, yield stress measurements gave variable results as illustrated in **Figure 2(18)**. Subsequently, measurement of the **degree** of yield stress was eliminated from the protocol balloted for D4684. Instead, yield stress was included only as a go/no-go type test with no basis of determining the precision necessary in interlaboratory comparison of gelation response.

Evident questions remain as to the ability of the method to respond to gelation **forming** below -20°C. However, these questions are really part of a larger question raised by the information in the ASTM round-robin report **(18)**. Even beyond the variation in yield stress response already discussed, it is apparent from the report data in **Figure 2** that some of the Pumpability Reference Oils used may at times show no gelation in the ASTM D3829 test (cf. PRO-09, 26, and 29 in **Table 2**). Moreover, two of these latter oils are shown in the ASTM report to be a pass or borderline fail in the viscosity test (PRO-09 $\cong$12.4Pa•s, PRO-29 $\cong$ 35.5Pa•s).

Summation of D4684 Protocol - The TP-1 protocol as modified to reduce cooling time and to eliminate measurement of the degree of yield stress in an oil became ASTM D4684**(18)** in 1987.

For flow-limited oils, depending on the temperature of test, D4684 has shown reasonable precision with values of 4-12% and 8-18% for repeatability and reproducibility, respectively at the 95% confidence level used by ASTM.

At this stage in its development, however, the method seems weak in not providing a way of establishing either the precision of detecting gelation or of determining gelation severity.

In summation, D4684 has remained essentially a two-step protocol with precision now expressed for oil viscosity and not for gelation.

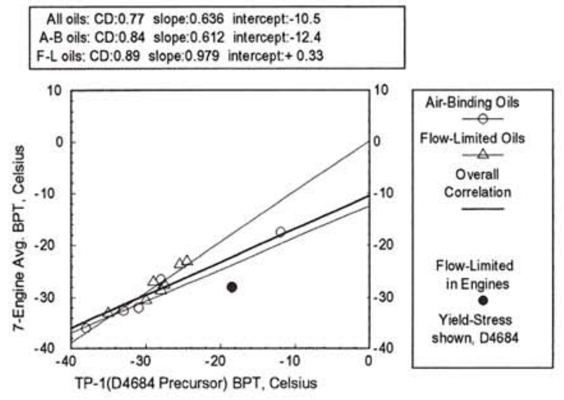
Correlation with ASTM Engine Pumpability - Correlation data using the oils in the ASTM engine pumpability study**(9)** is interesting and instructive. It would be expected that any dependable pumpability test should be capable of responding to problem oils produced by different cooling cycles since Nature can produce a variety of these cycles. From this point of view, the ASTM engine pumpability studies are simply another cooling cycle somewhat less demanding, in certain respects, than those producing the engine/oil field failures in 1980-81.

While, as noted above, the simplified D4684 protocol itself is not capable of generating BPT values, its predecessor protocol, TP-1, was used by Henderson et al. to obtain these BPT values for that protocol**(17)**. Engine BPT and MRV TP-1 BPT values from these sources are given in **Table 1** and plotted in **Figure 3**. This information permits development of correlation with the original ASTM engine pumpability Seven-Engine-Average BPT.

Interestingly, in this slower-cooling, more gelation-sensitive version of the MRV protocol, PRO-03 now showed gelation characteristics previously unrevealed in either the ASTM engine study or in the D3829 tests. While this apparent change in response to PRO-03 could be attributed to some change occurring to the oil over intervening years, none of the other oils in the ASTM PRO series showed such changes. It seems more likely to the author and others**(17)** that the oil (like the later field-failing oils) always has had a

Table 1 - ASTM Engine and TP-1 Data Compared

PRO No.	Engine Response		TP-1 Response		References
	Rheol.	BPT, °C	BPT, °C	Yield	
01	AB	-36	-38	none	(15,17,19)
03	FL	-28	-18.5	210	" " "
05	AB	-17.5	-12	490	" " "
06	FL	-23.5	-25.5	none	" " "
07	FL	-27	-29	-	" "
08	FL	-27.5	-27.5	none	" " "
09	AB	-26.5	-28	70	" " "
10	AB	-32.5	-33	none	" " "
11	FL	-30.5	-30	none	" " "
12	FL	-28.5	-28	-	" "
13	AB	-32	-31	none	" " "
15	FL	-33	-35	none	" " "
16	FL	-23	-24.5	none	" " "



Source: Ref. (17,19)

Figure 3 - *Correlation of MRV ASTM D4684 values of BPT with ASTM*

gelation-prone character too subtle to be revealed in either the ASTM engine pumpability study or the ASTM D3829 bench test method developed from this engine study.

Analyzing the data in **Figure 3** in comparison to **Figure 1**, it is pertinent to note that the flow-limited oils still respond with the near-unity slope and near-zero intercept of D3829. On the other hand, the air-binding oils show a much different relationship which reduces the overall correlation, slope, and intercept of the combined flow-limited/air-binding data (R^2=0.77, slope=0.64, intercept=-10.5°C). These data suggest a loss in ability of the new protocol to predict air-binding perhaps as a result of its lack of slow cooling at temperatures below -20°C.

ASTM D5133 - THE SCANNING BROOKFIELD TECHNIQUE -

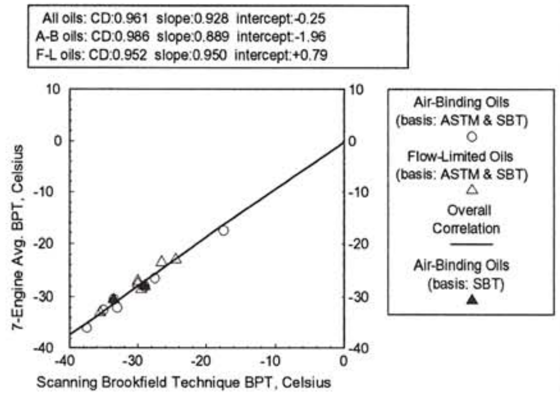
Considerable effort was also expended on the development of the Scanning Brookfield Technique[**(20,21,22)** - the latter reference is a SBT review paper]. This effort ultimately resulted in acceptance of the SBT as ASTM D5133 in 1990 **(23)**. The method continuously measures the oil viscosity over a predetermined temperature range of interest. From this data-stream several values can be generated including 1)the temperature at which a Critical Viscosity of 40,000cP (mPa•s) is reached, 2) the predicted BPT for the ASTM engine cooling protocol, and 3) two values uniquely associated with this test technique: a) the Gelation Temperature and b)the Gelation Index.

Gelation Sensitivity - Using a linear cooling rate of 1°C/h, the method was shown to be sensitive to gelation **(19,20, 21)** in engine oils. The SBT clearly responded to all of the field-failing engine oils and, in addition, showed that the oils had differing degrees of gelation. First studies**(13)** showed that the method predicted the temperature at which gelation formed in an engine and anticipated the temperature of air-binding in the engine by 5°C -- a relationship also shown by the behavior of a very similar oil in the engine tests of Stambaugh and O'Mara**(12)** [reviewed in detail in **(21,22)**].

Precision and Correlation - Precision in determining the temperature for a series of Critical Viscosities from 10,000cP (mPa•s) to 40,000cP (mPa•s), ranged from 0.65° to 1.09°C for repeatability and from 1.42° to 3.25°C for reproducibility depending on the Critical Viscosity chosen.

Correlation of D5133 with the ASTM Seven-Engine-Average BPT at 40,000cP is plotted in **Figure 4**. While the correlation to the engine BPT is not quite as close as D3829, both methods show a similar consistency among results from both air-binding and flow-limited oils -- a consistency not found in D4684 as noted above. That is, for ASTM D3829 and D5133, the data from the BPTs of both viscous and gelating oils fall on very similar slopes near unity in value and intercepts near zero. Overall correlation for D5133 was good (R^2=0.96, slope: 0.93, intercept: -0.25°C).

As in D4684, PRO-03 was also found by the SBT to have considerable gelation. In addition the SBT detected evident gelation with PRO-11, an oil originally blended to be 'soak-time-sensitive' (made to gelate) but which showed no response in the ASTM pumpability studies. (The most likely reason that PRO-11 was not shown as having yield stress in TP-1 BPT tests is that this oil's gelation starts below -20°C.)



Source: Ref. (22)

Figure 4 - *Correlation of SBT ASTM D5113 values of BPT with ASTM Seven-Engine-Average BPT using early pumpability reference oils.*

Correlation with D3829 and D4684 - Analysis of data has shown several instances in which the MRV methods disagree with one another and with the SBT in regard to gelation. In one case, it was shown that by reducing the cooling rate of the SBT, a more sensitive form of gelation was revealed.

Whether or not such gelation would affect the flow of oil from the sump to the screen is not clear in the light of the agreement of the SBT and the field-failing engine oils. Again, it is evident that new engine pumpability studies are needed.

In the main, however, the agreement among the three methods is reasonable **with flow-limited-type engine oils**.

EXTENSION OF SBT INFORMATION - GELATION INDEX AND TEMPERATURE -

In addition to finding gelation-response in all of the field-failing oils, the SBT data-stream could be further analyzed to more closely discriminate among the oils as to the degree of gelation and the temperature at which gelation formed **(21,22)**.

The latter information was obtained by generating parameters called Gelation Index and Gelation Temperature from a relatively simple analysis of the data stream. The approach was to calculate the first derivative of the MacCoull, Walther, Wright equation**(24,25,26)** for the viscosity-temperature data produced by the SBT**(21,23)**. Determination of the Gelation Index of the field-failing oils showed that the borderline value for these oils was 16. Oils having Gelation Indices above 16 would be expected to have given air-binding failures during the winters of 1980-81 with the engines of that period.

Correlation between Gelation Index and Yield Stress - It was also shown in the studies**(21)** that high correlation exists between the Gelation Index and the MRV yield stress. Again, the yield stress was taken from the measurements reported in the work by Henderson, et al.**(17)** using the MRV TP-1 method over the latter's range of ability to detect the formation of new gelation (down to a minimum of -20°C). The latter information confirmed that SBT Gelation Index is a measure of gelation severity. Gel Index has the potential of being considerably more precise than yield stress determined by the MRV TP-1 protocol and, of course, **must** be more precise than D4684 which has no precision at all. Thus, Gelation Index might be an effective overall measure of low-temperature pumpability if, as seems evident, avoidance of air-binding is the most critical concern.

ENGINE ZONES AFFECTING PUMPABILITY

THREE ZONES OF DIFFERENT SHEAR STRESS -

Figure 5 shows a sketch denoting three zones of the engine, each of which is believed**(22)** to require different rheological response from the engine oil and places different shear stress requirements for bench instruments to meet.

Zone 1 - Of these three zones, Zone 1, covering the flow from the sump oil surface to the screen, is the most sensitive to air-binding since it is here that the collapse of the column of structured oil into the pump pickup screen and tube generates air-binding. Very low shear stress/rate flow has been associated with this zone**(27,28)** and with the gelation-sensitive Scanning Brookfield Technique**(22,23)**.

Question of Zone 1 Shear Stress Level - A recent, interesting paper by Alexander**(29)** is at odds with the view of very low shear stress flow from the sump to the oil screen. His theoretical viewpoint is based on calculations assuming a yield-stress/macro-fracturing model which also requires sufficient flow to keep the oil screen covered. Since the work was not referenced in his paper, Alexander may not have been aware of the highly relevant experimental and theoretical studies detailed in a 1973 paper by McMillan and Murphy**(27)**. Their work led to the trenchant observation that **"... cavitation is not dependent strictly on yield stress. Cavitation occurs when the combination of yield stress and low-shear viscosity reduces the flow to the screen below that required to sustain continuous flow into the pump."** As indicated earlier in thepresent paper, McMillan and Murphy were one of the sources of information suggesting very low shear rates (0.01 to $0.1s^{-1}$) and, consequently, very low shear stresses of 0.3 to 3.0Pa at a viscosity of 30Pa•s in the gelated oil. Certainly, the coalescence of their experimental and theoretical work seems persuasive in considering the two, widely variant, points of view.

From another point of consideration, the 'ogee'-shaped viscosity-temperature curves generated by the SBT have very early-on been interpreted to indicate the development of an oil-enmeshing structure**(20)** limited in its rheology by the amount of structure capable of forming in the particular oil. The rheology of such a mass would evidently have both fluid and structural components. Consequently, it would have a degree of both flexibility and flow of the micro-structure under the influence of small forces.

Coupling McMillan and Murphy's studies and the close agreement of the SBT with engine data from all the PROs suggests that Alexander's theoretical assumptions should be expanded to include viscous effects stiffening a somewhat flexible structural component .

Zone 2 - Zone 2, from the screen to the pump is considered a higher shear stress zone primarily associated with flow-limited oil problems.

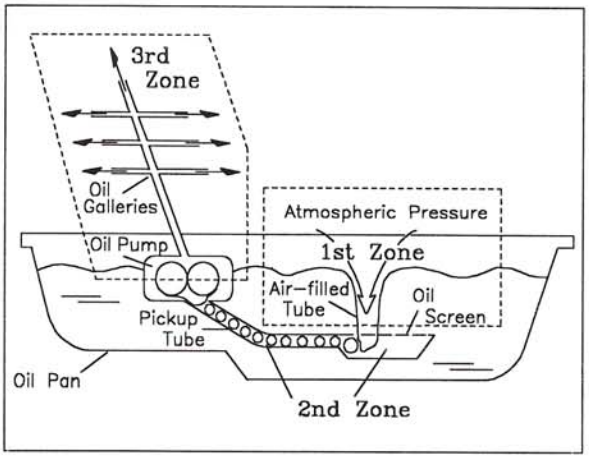


Figure 5 - *Three zones affecting engine oil pumpability.*

Calculation(7) and investigations **(7,28, 30)** indicate that shear stresses in this zone are in the order of 100-250Pa for a viscosity of 10Pa•s. The difference in shear stress between the MRV and the SBT seems not to seriously affect the correlation between the two instruments on flow-limited oils -- that is, both instruments have been shown to give similar viscosities with such oils**(20)**.

Zone 3 - Zone 3, from the pump to the lubricated surfaces turns out to be the highest shear stress zone of the three. Rough calculations (based on an indicated pumping pressure of 20psig or 138kPa at the pressure sensor and an oil gallery diameter of 0.25 inch or 6.35mm) give yield stress values at the gallery wall of approximately 2,000 to 4,000Pa depending on the location of the pressure sensor. Such shear stress levels fall well outside of the range of either the MRV or the SBT.

Questions Concerning Zone 3 - This third pumpability zone has, however, become the focus of a controversy **(31-36)**. Adequacy of D4684 in predicting flow to the cam lobes has been questioned. It is evident that neither D4684 nor D5133 should be expected to be correct in predicting flow behavior in Zone 3 except in the case of Newtonian oils. Both of these instruments would be expected to show poorer engine correlation with increasing non-Newtonian behavior in Zone 3.

THE PUMPABILITY/STARTABILITY BALANCE -

Those technical society members responsible for setting specifications for both startability and pumpability in SAE J300SEP80 also recognized that an engine should not be capable of starting if the engine oil could not be pumped. That is, it was considered important that pumpability should supersede startability -- lack of startability is usually an inconvenience; protracted lack of pumpability after starting the engine is a serious attack on either the pocketbook or the warranty.

Accordingly, when specifying SAE J300 limits for pumpability, the temperatures were set 5°C below the temperatures at which the oils should meet the viscometric limits for assuring startability. Thus, there was a *defacto* 5°C 'safety margin' built into the J300SEP80 Engine Oil Viscosity Classification which has been maintained ever since.

DISCUSSION OF THE PRESENT STATUS

Fuel injection and electronic timing have led to the development of viscosity-tolerant engines when called upon for dependable starting at low temperatures. Moreover, the development and OEM-encouraged use of SAE 5W-30 and 10W-30 engine oils further enhances low-temperature starting. The already excellent startability of these engines is being pushed to the limit to help automobile manufacturers meet ever more stringent emission and fuel-economy levels. It has been said that automotive engineers are focussing on starting and running the engine at high idle (2000-2500 RPM) within two seconds of turning on the ignition key. Under such circumstances, adequate pumpability is a markedly growing concern especially considering past experience with air-binding oils and the potentially catastrophic effects of unexpected cooling cycles.

Considering these facts on easier startability and higher idling speeds, and their combined effects on the dynamics of pumpability at low temperatures, a number of serious questions and considerations are raised. These will compose the next section of this paper.

THE QUESTION OF CRITICAL STARTING VISCOSITIES -

On the basis of past work associated with cranking and starting engines in the cold-room under various cranking speeds and oil viscosities**(4,37-41)**, the author estimates that Critical Starting Viscosities for modern engines may well be in the order of 10,000 to 25,000cP (mPa•s). This, in turn, means that engines could be started at temperatures at least 10°C lower than previously assumed using limits of 3500cP (mPa•s). If so, the consequence of such starting performance is a call to new ways of thinking about what is desired/required for acceptable engine oil viscosity at low temperatures. It is also a call to reconsider the startability/pumpability relationship. More broadly, it is a call to consider the whole area of the viscosity-temperature response of engine oils and how the modern engine is affected.

If engine oil gelation at low temperatures and the associated destructiveness of air-binding were not a factor, the low-temperature problem might resolve to a simple start/no-start relationship. That is, temperatures at which the oil would become flow-limited might also be temperatures at which the viscosity of the oil became too high to permit starting -- an oil-imposed protection again engine damage.

On the other hand, most gelation and consequent air-binding have been shown to occur at temperatures considerably higher than those associated with flow-limited behavior for the same SAE grade engine oil. Thus, it could be said that the ideal technical approach would be to eliminate oil gelation. This approach, if at all possible with advances in pour-point depressants, would retain all the benefits of lower starting temperatures with whatever associated improvement in fuel efficiency and lowered emissions might be generated.

But what is the reality of the market-place of today regarding viscosity at high shear stress and gelation? The next section will attempt to bring the answer to this question into view.

THE QUESTION OF LOW-TEMPERATURE PROPERTIES OF SAE W-GRADE ENGINE OILS ON THE MARKET -

Central to the whole question of the startability/pumpability balance is the reality of the marketplace. Data is fortunately available from the extensive engine oil database on oils collected yearly by the Institute of Materials **(42)**. The following information is presented with their permission and uses their data from the 1991 collection of 252 North American engine oils from the United States and Canada. While this database presents information on pumpability characteristics of engine oils using all three ASTM test methods, D3829, D4684, and D5133, only the latter data will be used because of questions regarding adequate sensitivity to gelation of the other two as well as a lack of ability to determine severity by D4684.

Gelation Index Range and Frequency - Considering that pumpability is more critical than startability and that air-binding is much more destructive and, thus, more of a concern than flow-limited behavior, the first information sought from the database was the Gelation Indices of all oils including those of single-grade SAE classification. This information is presented in the form of a histogram in **Figure 6** using a logarithmic ordinate for greater clarity. (It will be recalled that it has been shown that a Gelation Index of 16 was a borderline failure condition for the field-failing oils(**21,22**).)

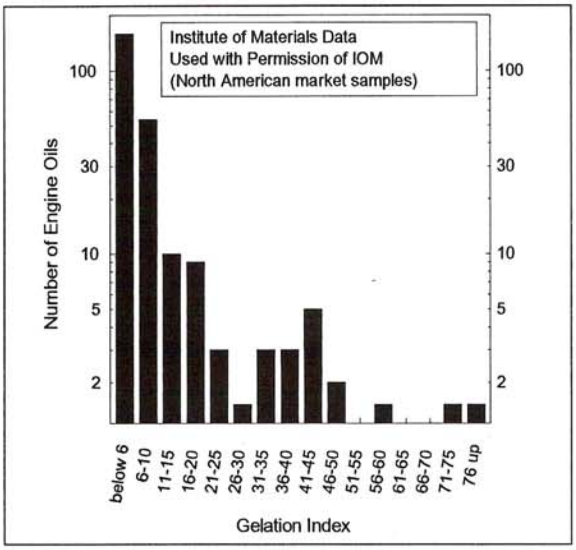


Figure 6 - *Distribution of Gelation Indices of engine oils collected throughout North America during 1991 (252 samples).*

Most of the oils collected (63%) have little or no evident structural response at low temperatures -- i.e. their Gel Indices are below 6, the normal response for ungelated mineral oils. A smaller percentage (20%) of the oils collected show Gel Indices between 6 and 10. Thus, these two categories account for 83% of the oils tested in 1991.

On the other hand, 17% of the oils tested had Gel Indices greater than 10 and **13% had Gel Indices greater than 15, ranging up to values well over 100!**

Gelation Temperatures vs. Gelation Index - The Gelation Temperature is the temperature at which the Gelation Curve reaches a maximum value called the Gelation Index of the engine oil.

Temperatures at which the engine oil gelates is one of the more interesting pieces of data produced by the SBT. Accordingly, the 1991 database was examined to determine the Gelation Temperatures of the oils. Results are shown in **Figure 7** on a logarithmic scale to include all data. Several points should be noted and commented upon:

1. As previously mentioned, most of the oils have Gelation Indices less than 6.

2. Most (76%) of those oils having Gelation Indices above 15 (the filled circles) showed these values at Gelation Temperatures above -20°C (or -4°F) and some of the Gelation Temperatures were as high as -8°C (+18°F).

3. The remaining oils (24%) having Gel Indices above 15, however, had Gelation Temperatures from -20°C to almost -35°C.

4. The sharp cutoff of data above -7°C is an artifact caused by the fact that the D5133 test is begun at -5°C and high values of Gel Index would not be expected to be registered immediately after beginning a run.

Thus, it is evident that significant gelation occurs from at least -8°C down to -35°C. There is no evidence that such levels of gelation are not meaningful at any temperature at which they occur despite assumptions to the contrary (**16,17**). Relevant information from engine pumpability studies can certainly clarify this issue. (The question of what composes relevant engine information will be discussed later at several points.)

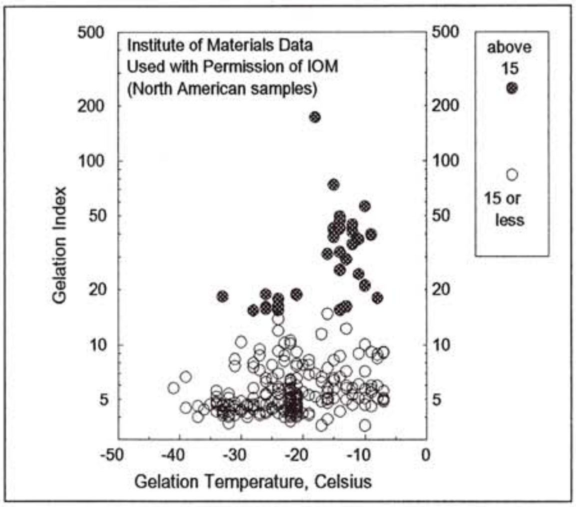


Figure 7 - *Cross-plot of Gelation Index and Gelation Temperature for all engine oils sampled from the North American market in 1991.*

CCS Viscosities at the BPTs of Highly Gelating Engine Oils - From the viewpoint of the questions raised earlier in this paper, the most critical piece of information regarding an engine oil is **the level of viscosity opposing startability at the borderline pumping temperature**. If this level of viscosity is lower than 10,000cP (mPa•s), the probability of starting below the borderline pumping temperature is high.

Once again the IOM database was queried and the CCS viscosity value at the predicted SBT BPT derived by using the MacCoull, Walther, Wright empirical equation (**24,25,26**). Correlation Coefficients (R) of at least 0.990 were shown for the various oils and gives confidence in the interpolated or extrapolated viscosity values. This information was of particular interest for those engine oils showing Gelation Indices above 15. **Figure 8** is a plot showing the

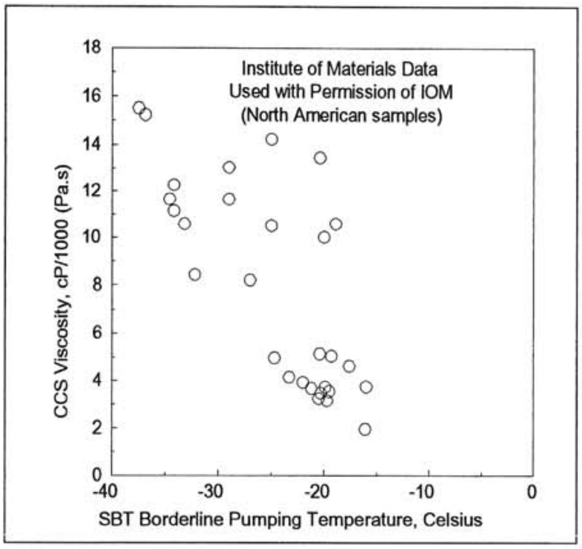


Figure 8 - *Cross-plot of SBT BPT and CCS values for engine oils with Gelation Indices above 15 (from 252 oils picked up on 1991 market).*

CCS viscosities at the SBT borderline pumping temperature for those engine oils having Gel Indices over 15.

This comparison is interesting and sobering. In general, the CCS viscosity values are surprisingly low for a number of the SBT borderline pumping temperatures shown. Half of the CCS viscosities are below 6,000cP (mPa•s) and only two are above 15,000cP (mPa•s) and, even so, both are less than 16,000cP (mPa•s). In other words, based on the engine/SBT BPT correlation and the assumption of a 15,000cP (mPa•s) Critical Starting Viscosity, it is very likely that the majority of these oils would permit the engine to start at the temperatures at which gelation would air-bind the engine (if the engines of today are at least as responsive to gelation as those of the early '80s). The real concern is that, not only may modern engines be much easier to start, but they also may be more vulnerable to air-binding as a consequence of fast idle effects on pumping oil from the crankcase.

THE QUESTION OF SAE SINGLE-GRADE OILS -

With indications that engines are capable of much easier starting and, thus, are tolerant of significantly higher viscosities, it is natural to question the gelation response of these oils at the higher end of the low-temperature range.

SAE EOVC Task Force Concerns - Over the last couple of years, the SAE Engine Oil Viscosity Classification Task Force (EOVC) has raised the question of starting/pumping temperatures of single-grade engine oils**(43)**. The issue is packed with uncertainties such as: should the low-temperature properties of single-grade oils be measured; if so, what would be the temperatures of measuring such properties; what is the frequency with which single-grade oils show gelation problems; etc.?

Selected Single-Grade Database by IOM - Relatively recently (in 1990) the EOVC asked the Institute of Materials to consider assembling and making available to those interested, a subsection of the massive IOM database. To generate and publish this information, the IOM had to re-analyze all of the single grade oils in its database. This Special Report on Single-Grade Engine Oils became available from the IOM in late 1990**(44)**.

For the single-grade report, IOM decided to use CCS values closest to 3500cP (mPa•s) at the nearest 5°C interval to determine the five-degree-lower temperature at which the MRV methods (D3829 and D4684) should be applied. (That is, if 3500cP occurred at either -23° or -27°C, the MRV methods would be run at -25°-[5°]= -30°.)

Significantly, it was shown that using the Scanning Brookfield Technique modified to start at temperatures above 0°C, some of the SAE 30 grade oils were vulnerable to serious gelation as high as -4°C (i.e.+25°F)**(45)** -- a temperature at which **most** new **or** older engines would be expected to start!

Gelation Index and Temperatures - Since the beginning of 1991 the IOM database has included the low-temperature properties of single-grade engine oils. A more recent analysis of the low-temperature properties of single grade oils in the 1991 IOM database was made by the author. The analysis is presented with the permission of the Institute of Materials.

In **Figure 9** Gelation Index values are shown versus Gelation Temperatures. While the evidence of serious gelation is limited to one oil, the SBT method begins at -5°C. If the method were started at higher temperatures such as +10°C or so, perhaps more gelation would be found at higher temperatures.

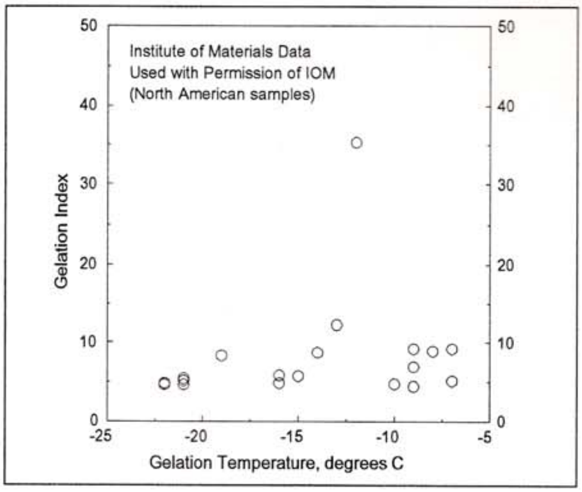


Figure 9 - *Cross-plot of Gelation Index and Gelation Temperature for a number of the SAE 30 engine oils marketed in North America in 1991*

As before with **Figure 7** on multi-grade engine oils, it is evident from **Figure 9** that gelation is not limited to particular low-temperature ranges. It is also evident that some SAE 30 oils are essentially gelation free (i.e. have Gelation Indices less than 6) down to at least -22°C.

On the basis of these single-grade engine oil studies, questions concerning the potential need for requiring some form of low-temperature classification for such oils have been raised by the SAE EOVC Task Force to its parent Fuels and Lubricants Subcommittee 1**(46)**. Response will be a matter of high interest in the continuing development of J300.

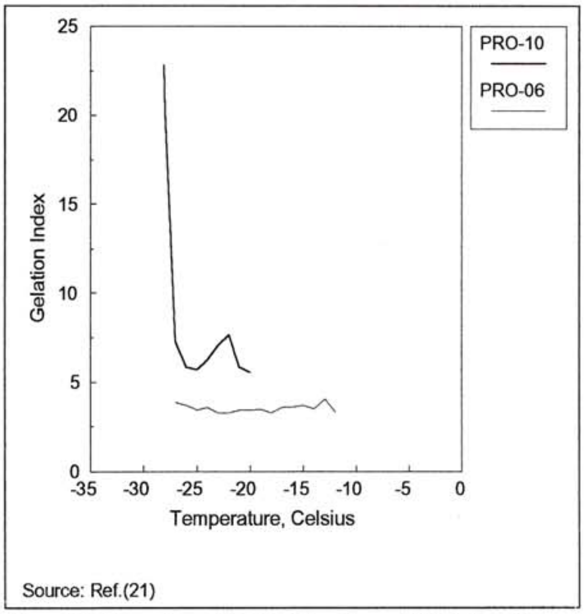
THE QUESTION OF RAPID STARTING AND HIGH IDLING SPEED EFFECTS -

Rapid starting and high idling at low temperatures would be reasonably expected to place greater demands on pumpability of the engine oil. In this regard, there are interesting, if very limited, data.

In the previously-mentioned breakthrough pumping studies of Stambaugh and O'Mara **(12)**, they briefly investigated the effect of speed on the pumpability of two engine oils, PRO-6 and PRO-10. Normally, their engine tests were motored at 1530 RPM. However, in one sequence they decided to motor a 1.6Lengine at the manufacturer-established fast idling speed for these engines of 2200 RPM.

At its BPT of -23.5°C, the flow-limited PRO-06 confirmed the lower speed BPT. With the air-binding PRO-10 at its BPT of -33°C in the sump of the 1.6L engine, after fifteen seconds into the 2200 RPM, a major engine failure occurred. The authors commented that the failure was very reminiscent of reported field failures and associated the failure with the more stressful mode of operation at the higher idling speeds.

Looked at from the view of the SBT, PRO-6 and PRO-10 are quite different in rheological characteristics. Gelation Temperature and Gelation Index studies with the SBT have shown [cf. **Figure 10 taken from (21,22)**] that PRO-6 (a 20W-50) was indeed flow-limited throughout its range while PRO-10 (a 5W-40) began to **sharply** gelate at -28°C. From this and the shape of the Gelation Curve in **Figure 10**, the SBT would predict **serious** air-binding problems beginning at -33°C for PRO-10 but only marginal problems for PRO-06.



Source: Ref.(21)

Figure 10 - *Comparison of Gelation Index Curves of PROs 06 and 10.*

This explanation does not contradict their conclusion that the BPT doesn't seem to change with higher idling speeds but does suggest that the **severity and promptness** of failure might very well increase when there is more need for adequate oil supply to stressed rubbing surfaces.

In any case, it is reasonable to expect that if a given engine oil gelates to some degree in the sump at a given temperature, the demand placed by higher idling speeds for faster flow from that region will exacerbate the tendency for air-binding and more readily lead to catastrophic engine failure.

THE QUESTION OF CAUSES OF GELATION IN THE ENGINE OIL -

Wax and Other Sources of Gelation - Gelation is often said to be associated with wax-crystal formation **(6,16,17,47,48,49)**. While this is undoubtedly so, other important forms of gelation, such as wax-polymer and additive interactions, have also been demonstrated **(20,50,51,52,53)** as being uniquely and/or collectively involved. To state the point again, these facts and the evidence provided by the SBT do not support the premise **(16,17)** that gelation important to engine oil pumpability is restricted to temperatures above -20°C.

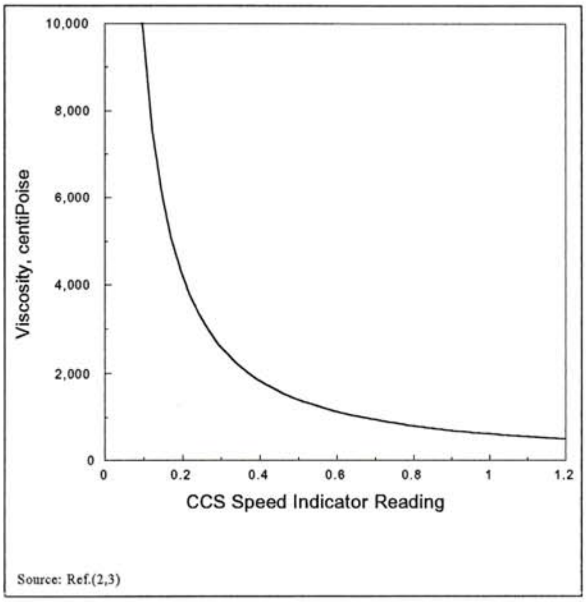
Importance of Measuring Gelation Forming Below -20°C - In support of the counter-premise that gelation below -20°C **is** important, it should be noted that most of the air-binding oils in the ASTM engine pumpability study **showed** air-binding response at temperatures below -20°C and PRO-01,10,11, and 13 **began** gelating below -20°C.

With the advent of lower-viscosity, easier-starting engine oils formulated from the more highly paraffinic, good VI, hydro-treated base oils, the aforementioned premise that gelation below -20°C is not important, may become even more questionable until, and unless, engine pumpability data are gathered to determine the issue.

THE QUESTION OF HIGH SHEAR STRESS VISCOMETRY -

The CCS and Its Range vs. Engine Starting Viscosity - Over its years of faithful service, the Cold-Cranking Simulator has shown that its most sensitive range is from approximately 500 to 7,000cP (mPa•s) as shown in **Figure 11**. Outside of this range, the values follow asymptotic loss in precision. If Critical Starting Viscosities must be measured in the 10,000 to 25,000cP (mPa•s) range, this would seem to require a new range of high shear stress viscometry.

One Approach: Validity of Extrapolating CCS values - However, returning again to low-temperature data from the IOM database, the CCS data reported in this database were generated by a more precise technique than called for in the ASTM methods. In the process of analyzing these so-called 'Step-Scan' CCS data for **Figure 8**, it was also possible to test the precision of applying the MacCoull, Walther, Wright viscosity-temperature equation **(24,25,26)** to Step-Scan CCS low-temperature data. It was found that the mean and standard deviation of the value of R^2 for these oils was 0.9970 and 0.0017, respectively. Such values suggest reasonable confidence in extrapolation to higher viscosities



Source: Ref.(2,3)

Figure 11 - *Hyperbolic variation of viscosity with speed for the CCS.*

as well as a means to develop such information using the Step-Scan CCS technique.

THE QUESTION OF A NEW STARTABILITY/ PUMPABILITY BALANCE -

It seems apparent that if startability is improved by -10°C, pumpability must become even more of a critical matter. More evidently, in considering the various aspects of pumpability, it would seem to be of major importance to have precision and sensitivity in measuring the gelation level of potentially air-binding engine oils.

THE QUESTION OF THE IMPORTANCE OF GELATION MEASUREMENTS VS. SIMPLE VISCOSITY MEASUREMENTS -

As shown in the 1980-81 epidemic, the insidious nature of an oil having an air-binding response is that it may occur very unexpectedly under certain cooling conditions but not in others. Moreover, if gelation forms, it has been shown to form more readily at relatively low viscosity levels and, thus, at relatively higher temperatures in the low-temperature range. This would be expected from the nature of gelation in which the propinquity of the gel-forming molecules is aided by relatively rapid migration through the fluidity-maintaining molecules (a process enhanced and regulated by the artificial stimulus of the turning rotor of the SBT).

In contrast, flow-limited behavior is fairly predictable from viscosity measurements at higher temperatures (e.g. using the MacCoull, Walther, Wright equation **(24,25,26)** as discussed previously). Thus, flow-limited behavior is usually encountered at lower temperatures and at viscosities at which starting might also be a problem.

To make the point once more, it is quite evident that, of the two forms of pumpability difficulty, air-binding is the most deadly and creates most difficulty for the easier-starting engine. Commensurately, then, the greatest need is for sensitive gelation measurement on the bench.

THE QUESTION OF SINGLE-TEMPERATURE PUMPABILITY MEASUREMENT -

Earliest techniques in measuring pumpability showed the importance of anticipating that gelation is unpredictable. ASTM D3829 required determination of the borderline pumping temperature plus measurements at two higher temperatures. With easier cold starting, the problem is compounded. Protection against gelation failures would seem to eliminate use of single-temperature specifications except for viscosity limits. Effective protection from gelation effects will require multitemperature or temperature-scanning techniques to avoid the unexpected occurrence of sudden and severe gelation. This problem of single-temperature 'blindness' has already been reported regarding the rheology of an SAE 20W-50 in which the oil was a clear pass at its test temperature of -15°C in D4684 and a severe failure if run instead at -20°C. The oil was found in the field in the 1991 survey by the Institute of Materials as shown by their SBT D5133 data with a Gel Index of more than 74. In view of the possible consequences, questions have been raised but only partially resolved regarding changes in D4684.

THE QUESTION OF LUBRICANT FLOW FROM THE PUMP -

Next to the ability of the oil in the sump to flow sufficiently rapidly to supply the oil pump with sufficient quantity, flow to the lubrication sites -- the aforementioned Third Zone -- is most critical. If the forces brought to bear on engine components by higher idling speeds are to be contained without engine damage, timely and reliable lubricant flow to the wear surfaces must take place.

Operating Shear Stress - As previously noted, calculations of operating shear stress in this zone (2000 to 4000 Pa) indicate that viscometric performance in this zone is essentially unspecified regarding bench tests. Neither the SBT nor even the MRV operate at high enough shear stress to properly define fluid flow in this zone except as the oil approaches Newtonian behavior. However, the MRV produces more relevant shear stresses in this Zone than the SBT. The latter effect may explain some of the correlation of the MRV with cam lobe oiling time**(19)**

Perhaps, using the approach of McMillan and Murphy**(27)** or a further modification, it would be of value to consider correlating the flow of polymer-modified oils from the engine pump with new bench tests run at the appropriate temperature and shear stress.

THE QUESTION OF DIESEL ENGINE PUMPABILITY -

Present Technical Dialogue - Lubrication of reciprocal engines, of course, is not limited to spark ignition, automotive engines. Recent pumpability concerns in regard to heavy duty diesel engines have been expressed regarding comparative pumpability response in Zone 3 with oils having different VI Improvers**(29-34)**. While this particular issue is another facet of pumpability, it is important to consider that, in general, flow **from** the pump to the lubricated surfaces is a flow-limited form of pumpability unless flow **to** the pump is air-binding.

The aforementioned technical controversy also involved questions regarding the use of the MRV to predict flow rate in this zone. This part of the debate begs the real question of whether or not an instrument applying significantly lower shear stress should be expected to provide relevant correlation. The controversy is additionally compounded by the use of different oil pressure yardsticks in the technical debate.

Concern with Higher Temperature Gelation - A much greater threat to heavy-duty Diesel engines occurs when strong gelation occurs at temperatures and at cranking viscosities where the Diesel engine can be relatively **readily** started. Unfortunately (or perhaps prudently, considering the cost of these engines), all of the reported low-temperature pumpability tests on these engines seem to have been conducted with flow-limited conditions.

It is evident that air-binding engine oils are in the field which will experience gelation as high as +4°C (+24°F) so it would seem reasonable to test such oils in the heavy-duty Diesel engines before drawing conclusions about correlation with bench tests.

THE QUESTION OF ALTERNATE FUEL EFFECTS ON LOW-TEMPERATURE ENGINE OIL RHEOLOGY -

Very recent studies**(54)** of low-temperature behavior of used engine oils in engines powered by alcohol-containing fuels have clearly shown that the rheology of these used oils will be quite different than with conventionally-fueled engines.

At this time the work is simply too new to have generated any salient information that can be compared to mineral oil behavior. Obviously, this is an important area for low-temperature studies.

THE QUESTION OF USED OIL EFFECTS IN GENERAL -

Over the years in which the technical community has observed the effects of engines on the low-temperature properties of their engine oils, reports of both improvement and worsening of performance have been made. Confirmation with definitive studies of effects of both solid and liquid contaminants such as fuel, would be helpful particularly in view of improved startability.

Fuel dilution effects increasing the air-binding potential in Diesel engines were reported in Europe during the early '70s. It would seem prudent to consider this possibility by admixing Diesel fuel and engine oils and analyzing the gelation potential of such mixtures.

THE QUESTION OF BASE STOCKS -

Two engine oil base stock properties have driven the refining and formulation procedures over the years. One has been the oxidation resistance which affects engine cleanliness and durability and the other has been the viscosity-temperature relationship which affects high temperature hydrodynamic lubrication and low-temperature starting. Both are intertwined since those paraffinic molecules which are comparatively stable under oxidation conditions are often also comparatively high in Viscosity Index. However, these same molecules are also more prone to form structures in the oil. Consequently, the high temperature benefits are, to some degree, offset by low temperature needs for dewaxing treatment and additive costs.

Today, with deep hydrotreating of both virgin and rerefined feedstocks, even more highly paraffinic base stocks are being produced. With these, even at presumably 'normal' pour point depressant treatment levels, certain cooling conditions may trigger gelation response not previously encountered with less paraffinic, more naphthenic stocks.

However, the situation can be viewed from the point that, with the growing ease of low-temperature startability, some of the forces pushing toward use of higher VI base stocks are lessened. Consequently, other sources of basestocks can now be considered with the goal of developing blends bringing more control of gelation even though presenting higher viscosities at low temperature.

THE QUESTION OF ADDITIVES -

Engine oil additives can be divided into those affecting the viscosity-temperature relationship (VI Improvers); those affecting the tendency toward crystal formation and gelation at low-temperatures (Pour Point Depressants); and those affecting the oxidation, dispersancy, and wear resistance.

Effect of Better Startability - Easier low-temperature starting provides a basis which, as noted above, can be applied to modify the choice of base stocks and their blends. This opportunity to use alternative base oils, will unavoidably impact on choices of additives. It is reasonable to consider that broader base stock blends and appropriate additive development and selection may bring about significant changes and benefits in 'best-of-all-worlds' engine oil formulations.

Additives and Pumpability Control - The role of additives in the area of low-temperature flow has been studied intensively both in regard to engine cranking/starting and pumpability under the influence of viscosity modifiers (Viscosity Index Improvers and Pour Point Depressants) **(1,4-9,20,22,37-41,50-53,55-59)**. However, additives designed for purposes other than viscosity modifiers can affect pumpability. That is, depending on their design (and the diluents used to carry them into the oil formulation), additives used to control oxidation, deposits, corrosion, etc. may also play a role in developing or inhibiting gelation**(20)**.

DISCUSSION

GENERAL -

On the basis of the questions and data presented, it is evident that the time has come for a wide-ranging reconsideration of the low-temperature relationship between the engine oil and the engine. Realistically, with low-temperature startability so much improved and dependable, the more critical problem seems to be to properly measure and specify the pumpability of engine oils.

Gelating oils are likely to be the source of most low-temperature pumpability problems today and in the future. Since the beginning of the IOM North American database, such oils have always been present on the market as shown by the Scanning Brookfield and MRV TP-1 data which are part of that database. Although determination of the Gelation Index and Temperature did not begin until 1991 in the IOM database, the severity of the SBT curves shown in the IOM Primary Reports can be estimated by comparison to the 1991 Gelation Index data. This analysis is shown in **Figure 12** and a reasonable conclusion from analysis of the data is that not only has gelation been relatively common in past years, but it seems to be increasing in frequency and severity.

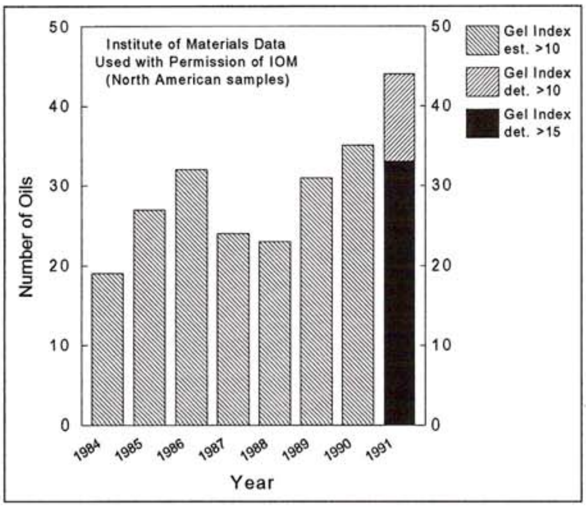


Figure 12 - *Gelated engine oils on North American market as determined by the Scanning Brookfield Technique (first seven years estimated from SBT charts in Primary Reports of IOM database).*

As previously mentioned, one of the possible reasons for this increase in number and severity may be the increasing availability and use of heavily hydrogenated -- and thus more paraffinic -- base stocks.

MEASUREMENT OF CRITICAL STARTING VISCOSITIES -

The Need - There is no question of the virtually immediate need to determine the Critical Starting Viscosities of modern engines. It is quite clear that this information is essential in determining the temperatures at which to measure both high and low shear stress viscosity of engine oils and to establish new criteria of classification for their low-temperature performance. The greatest benefit, of course, is in knowing the temperatures at which the engine must be protected against the effects of low-temperature pumpability failure.

Viscometric Correlation - Once engine information on Critical Starting Viscosity is had, the issue of how, and with what precision, measurements of the associated high shear stress viscosity is to be made, can be decided. As previously mentioned, it is possible the Critical Starting Viscosities for these engines will be found so high and the associated temperatures for SAE 5W and 10W grades so low, that high shear stress measurements capable of handling such viscosities will be considerably less of a concern than low shear stress measurements of the gelation rheometry. It is possible that with the results obtained, new engine/viscosity correlation studies may be necessary.

It is reasonable to consider that at the high shear stress applied by the Cold-Cranking Simulator, values obtained at higher temperatures and thus lower viscosities could be extrapolated to gain information at lower temperatures.

Testing Protocol - The nature of cold-room measurements of starting using either engine bucks or automobile chassis rolls really offers no great difficulty in regard to cool-down protocol as long as the engine and oil are at the cold-room test temperature and battery power and fuel are carefully chosen for optimum startability. Efforts to start at several progressively lower temperatures with oil change between tests will establish the Critical Starting Viscosity. At the same time, of course, other parameters can be measured (excluding pumpability measurements associated with Zones 1 and 2 which will require very careful, perhaps multiple, cold-room cooling protocols). The test protocol should include the shortest time possible the ignition key may be held on after engine firing commences.

BORDERLINE PUMPING TEMPERATURES OF MODERN ENGINES -

The Need - Much has already been said in this paper and elsewhere of the importance of determining gelation tendencies of engine oils. With low-temperature startability not only under good technical control but, at high idle, capable of laying additional stress on the pumpability of gelated engine oils, the need is high for broad temperature range measurement of the onset temperature and degree of gelation.

First work by the ASTM in determining the borderline pumpability temperatures of the Pumpability Reference Oils provided highly useful information still of value after nearly two decades. The BPT approach is very helpful in determining response of the oils which will be used in developing the rheological correlation which is not only viscometric but seems to be a combination of viscosity, structure and structure modification by additive components.

The Problems - There are several problems to be faced in developing such a study and its resultant data. The first problem is the tendency to presuppose what should be expected from the study and thereby miss incorporating salient factors. This is exactly the evidence of the first ASTM study; the lesson taught is to closely examine technical preconceptions and bias. Often, the higher the confidence in preconceptions, the greater the chance of bias and error -- consequently, the greater the need to discuss other viewpoints and approaches -- to seek answers rather than confirmation.

Example of the Problem of Development of Engine/Bench-Test Correlation - A recent motored engine pumpability study of eight 5W-30 engine oils conducted in a cold-box is a good example of the way in which bias is inadvertently generated**(60)**, and is thus worth some discussion. In these studies, Henderson (one of the developers of the MRV TP-1/D4684 **(17)**) wished to contrast the correlation of the MRV TP-1/D4684 and the SBT D5133 using his engine test. To do so, he assumed that the cooling curves of the two bench instruments were quite important in generating gelation in the engine, rather than letting engine results show the way to the use of the instruments.

Accordingly, he looked for correlation between chosen test data from his engine (time to build 120kPa pressure in a cam tower) and, alternatively, MRV TP-1/D4684 and SBT D5133 **viscosities** using the cooling curves of each bench test (minimum rate: 0.33°C/h down to -20°C, and 1.0°C/h throughout the temperature range of interest, respectively). The fact that the continuously stirred SBT was developed to allow a cooling rate of only 1.0°C/h to show correlation with generally more slowly cooled engines in the field apparently went unnoticed -- as perhaps did the fact that the limited range slow-cooling rate for D4684 had been chosen on the basis of test expediency with no expectation of meaningful gelation below -20°C. In short, an engine test not very likely to develop significant gelation at the temperatures of test was first compared with one bench test also not likely to develop gelation under the conditions and then compared with another bench test likely to show gelation.

The missing pieces of evidence were 1) whether any of the chosen 5W-30 oils had sufficiently high Gelation Indices to possibly fail in this engine test protocol and 2) that, even with highly gelating engine oils, whether the engine test **could** produce air-binding BPTs similar to those generated in the -25° to -35°C temperature range in the ASTM engine pumpability studies **with engine oils starting gelation below -20°C**.

Unfortunately, to compound the uncertainties in this motored engine test setup, the idling speed (1600-2000 RPM) of the engine could not be reached for 25-30 seconds. By that time (as the author showed), warm oil was already beginning to return to the sump and cycle back to the intake screen -- destroying any opportunity for air-binding (if such existed). Thus, without some evidence of air-binding BPTs similar to those produced in the ASTM engine studies at temperatures of -25° to -35°C **on oils beginning gelation in the range of -20° to -30°C**, there is no indication that the engine setup **would/could** produce evidence of gelation at and below -25°C, particularly with the slow acceleration to idle and relatively rapid return of heated oil. Despite these uncertainties, the data were used to report good correlation between the MRV D4684 and cam tower pressure in the engine (Zone 3). Simultaneously, the remaining data reported much poorer correlation with the SBT D5133 (a Zone 1 instrument) using viscosities sometimes extrapolated from his modified D5133 bench test setup. In view of the selected test conditions, neither result is unexpected and, in this author's opinion, neither is particularly relevant to the real world conditions of subtle gelation formation.

The primary question in this particular study is 'why develop an engine test to imitate the cooling curves of instruments'? If, as has been found in the ASTM engine pumpability studies, imitation of a relatively well-conceived engine test protocol **on the bench** can yield erroneous prejudgments in understanding Nature's capriciousness, certainly running an **engine test** to imitate a **bench test** has very little to recommend it.

The underlying requirement and the point of this portion of the paper would seem to be that engine BPTs must first be established to determine if the engine setup is valid in reasonably representing the performance desired in the field. Then bench tests can be appraised -- regardless of whether they 'seem' to imitate Nature.

A second point well illustrated by the above study is that simply applying an engine test of some sort will not likely provide relevant data unless the protocol, reference oils, engine response parameters, etc. are not only well thought out but frequently challenged.

The Problem of Reference Oil Selection - The second problem is selection or generation of reference oils. Again, the tendency is often to exclusively generate black and white comparisons. At least as important is to also develop oils of borderline response in, as one example, forming a gelated condition. Oils of extreme response are effective for defining the field -- oils of borderline response are best in defining the technique and/or the instrument of measurement, whether engine or bench device.

The Problem of Engine Test Conditions - As already shown in the discussion of engine/bench-test correlation, the third problem is encountered in selecting cooling conditions and, in the case of engine test stands particularly, giving them meaningful exposure to chilling conditions without biasing the test. Most important is the selection of initial temperature(s), cooling rate, soak periods, and the general pre-preparation of the oil and engine for the test. Assumption of a particular cooling profile from past experience, such as the Sioux Falls Cycle**(12)**, is helpful in building a technical bridge with the past but does not assure that this or any one protocol will reveal all gelating oils of today in all engines. While not generally known, PRO-30 (an SAE 15W40) **did not fail on the Sioux Falls Cycle but dramatically failed when steadily cooled slowly from about -5° to -20°C (20).**

The Problem of Defining Salient Measures of the Engine Effects of the Rheology of Engine Oils - The fourth problem is the selection of measurements of flow behavior as indicated by oil pressure curves, development of cavitation in the sump or in the pump, first appearance of oil in the camshaft area, etc. Definition of oil performance in an engine pumpability test ultimately defines the test instruments and oils of the future.

Suggested Preliminary Study - In view of some of the aforementioned problems and the costs of sorting through cooling protocols, it would seem expedient to run cold-box tests such as those reported by McMillan and Murphy**(27)**. This could save much time and expensive cold-room testing.

A PROPOSED LOW-TEMPERATURE CLASSIFICATION SYSTEM

PURPOSES OF PROPOSAL -

For purposes of generating a technical dialogue on the information and viewpoints presented in this paper and others on the subject, a proposed low-temperature portion of the SAE J300 Engine Oil Viscosity Classification System for spark-ignition engines is shown in **Table 2**.

The proposed revision assumes a Critical Starting Viscosity of 15,000cP for the modern engine. It requires use of at least the CCS and SBT. It also includes the MRV method D4864 but only for flow-limited oils. In addition, recognizing the concern with Zone 3 flow it suggests what seems to be an appropriate viscosity value for this shear stress range using an as yet unknown viscometer.

Table 2 - Proposed Low Temperature Classification

SAE Grade	Startability		Pumpability				
			Flow to Pump		Gelation		Flow to Engine
	Temp. °C	Viscosity cP(max.)	Temp. °C	Viscosity cP(max.)	Temp. °C(min.)	Index (max.)	Viscosity cP(max.)
Bench Test Methods:		(1)		(2,3)	(3)	(3)	(4)
0W	-35	15,000	-35	30,000	-40	<6	20,000
5W	-25	15,000	-25	30,000	-30	<6	20,000
10W	-20	15,000	-20	30,000	-25	<6	20,000
15W	-15	15,000	-15	30,000	-20	<6	20,000
20W	-10	15,000	-10	30,000	-15	<6	20,000
25W	- 5	15,000	- 5	30,000	-10	<6	20,000
20	0	15,000	0	30,000	- 5	<6	20,000
30	5	15,000	5	30,000	0	<6	20,000
40	10	15,000	10	30,000	5	<6	20,000
50	15	15,000	15	30,000	10	<6	20,000
60	20	15,000	20	30,000	15	<6	20,000

Footnotes:

(1) ASTM D5293 (extrapolated)
(2) ASTM D4684
(3) ASTM D5133
(4) ASTM D????

From the various observations made earlier in this paper and the statements and work of others, the proposed low-temperature classification in **Table 2** seems to have several advantages. Among these are that it

1. recognizes the impact of gelated oils on present and future engine operation and gives a method of controlling unexpected gelation at starting temperatures.

2. corrects the system for the improvement in ability to start at lower temperatures and thus tends to eliminate the present danger of being able to start engines with oils that can't be pumped -- primarily those with gelated response.

3. includes single grade engine oils whether W-graded or not.

4. suggests the need for a viscometer to measure Zone 3 pumpability response and suggests an appropriate level of viscosity .

5. Continues to apply the CCS by utilizing extrapolation to lower temperatures.

6. Uses the present pumpability-measuring viscometers in their areas of greatest strengths.

Again, it should be emphasized that the system of **Table 2** is proposed primarily to generate thinking and dialogue on the need for a major change in the starting/pumping relationship -- a need which has already been recognized by the technical community and on which some dialogue is already taking place.

Testing the proposed low-temperature classification system in **Table 2** by comparison to the data in the 1991 IOM database shown in **Figure 7**, the proposed system successfully flags all gelated oils at the level of a 15,000cP (mPa•s) Critical Starting Viscosity.

It should be noted that the purpose in specifying a maximum Gel Index 5°C below the indicated temperature for flow-limited pumpability is that gelation would in this way be restricted to temperatures well below the Critical Starting Viscosity -- whatever that may turn out to be when industry-proposed low-temperature engine starting studies are completed.

SUMMARY

The marked improvement in low-temperature starting of spark-ignition engines transfers virtually all low-temperature concerns about engine operation to pumpability of the oil. In particular, improved startability has sharpened concern about the insidiously hidden characteristic of gelation-prone oils that have the potential for wiping out the engine in a few minutes of operation.

A number of critical questions have arisen over the last two years and these and several more are noted in the Discussion. Most of these questions deserve carefully studied answers rather than the brief comments given for most of them in this paper. While many oils are gelation-free, last year's collection of marketed oils appearing in the IOM North American Database on Engine Oils shows that a number of these oils have gelation levels equal to or exceeding those oils which failed in the field at the beginning of the 1980s.

This fact does not infer that today's or tomorrow's engines are, or will be, as vulnerable to gelation but there is also no information or reason to indicate that they will not be as vulnerable -- or even more so, under high idling conditions.

The appropriate path seems to be, using today's understanding, to set up better protection in the SAE Viscosity Classification System by first recognizing the simultaneous impacts of easier starting and higher idling engines, and the field presence of gelation-prone engine oils. The present system with its startability-bias should be changed to a gelation-bias to reflect the gains in startability and to protect the engine against the consequences of air-binding.

What this new low-temperature balance between starting and pumpability will bring in the way of base stocks, additives and formulation strategies, is difficult to predict but there will be many possible approaches and opportunities to capitalize on such improved startability.

However, unless, or **until**, new studies of startability and pumpability are completed and applied as a basis for specifications, **"Perhaps the most prudent course is to assume that, if any instrument gives indication of strong gelation, air-binding should be expected in the engine ..."(20).**

CONCLUSIONS

1. The present SAE J300 Engine Oil Viscosity Classification System at lower temperatures has been, and presently is, biased toward startability for dependability and convenience in cold weather.

2. The automobile has become significantly and progressively easier to start at low temperatures as a consequence of fuel injection, electronic timing, and other advances.

3. Easier-starting engines are more susceptible to pumpability difficulties because they can start in lower temperature regions in which a previously acceptable oil may no longer flow properly to or from the oil pump.

4. Gelation-prone engine oils are most likely to permit the engine to start but not pump and thus have the greatest potential for engine damage.

5. Consequently, it is suggested that the SAE Engine Oil Classification should become gelation-biased for engine protection.

6. Easier starting has lowered the starting temperature for single-grade oils as well, and bench data on such engine oils suggests that gelation problems can readily affect these oils often used in heavy-duty Diesel engines.

7. Under the quick-start, high-idle conditions design of modern and future engines (as part of the effort to reduce emissions and increase fuel economy), pumpability problem oils (particularly those susceptible to gelation) may fail even more readily and severely at low temperatures.

8. A new low-temperature section of the SAE J300 is proposed to eliminate the startability-bias of the present system and more closely focus on engine oil pumpability. The proposal includes a relaxation of **startability** requirements by increasing the maximum high-shear-stress viscosity levels to 15,000cP (mPa•s) and introduces both the SBT Gelation Temperature and Index as gelation controls.

9. While, as presently designed, the Cold-Cranking Simulator, seems to be most useful in range and precision when evaluating the viscosity of oils between 500 and 7,000cP (mPa•s), in order to reach the level of 15,000cP (mPa•s) proposed for the low-temperature classification, the author suggests the use of extrapolation using a series of viscosity determinations and the MacCoull, Walther, Wright equation. Precision was shown to be acceptable.

10. Given a rigorous winter, the situation seems ripe for another 1980s-type debacle if appropriate action is not taken to determine the Critical Starting Viscosities and Borderline Pumping Temperatures for engines and to redetermine the degree of correlation of bench equipment.

11. Cold-room studies to provide new measures of startability and pumpability must be designed with a great amount of forethought and few, if any, preconceptions to avoid repeating the past experience of designing a method satisfying such technical preconceptions but failing to satisfy Nature. To avoid the time and expense of searching out different cooling protocols in the cold-room, it would seem prudent to develop such protocols first in cold-box studies.

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