A More Precise Determination of Gear Oil Viscosity at Low Temperatures

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Automotive gear lubricants play a critical role in transferring power between mechanical devices. Today these lubricants seldom draw the interest of today's modern equipment user. This is in part because most equipment employ closed lubricant systems that a user has little contact with until there is a problem or failure. Since the gear lubricants operate in a closed environment, they are not as exposed to the hostile environment that an engine oil sees. However, there are aspects of operation that stress a gear oil as much or more than an engine oil is stressed. The stress is just applied in a different way.

Gear boxes and transmission cases are designed so that the gears are either partially or fully immersed in the gear oil. In either case, the rotation of the gears is used to circulate the oil. The rotation of the gear teeth refreshes the oil coating between each tooth-to-tooth engagement. It is this fresh layer which cools the surface of the gears between engagements. This fresh lubricant coating also replenishes the anti-wear additives on the gear tooth's surface. This fluid coating with fresh anti-wear additives protects the gear teeth from metal to metal contact as the gear teeth slide past each other to transfer power from input to output. When two metal surfaces slide over each other at high loads with insufficient lubrication, metal to metal contact is likely. The metal to metal contact will result in not only increased wear but also galling and pitting. These surface changes will result in slowly increasing loads as the contact area decreases. These change will lead to excessive heat and wear or even breakage of the gear teeth. Thus it is critical for the gear lubricant to have sufficient fluidity so the working areas are covered at all times by a fresh coating of lubricant.

Low temperature fluidity is a critical aspect of whether a fluid is fit for purpose. Even though low ambient temperature operation is typically a very small portion of a gear boxes service life. Poor fluidity in cold weather operation can be a significant impediment to maintaining a fluid coating on gear teeth. With an excessively high viscosity, the rotating gears cut a channel through the thick lubricant without refreshing the fluid coating on the teeth. When this occurs, the gear teeth quickly lose their lubricant coating. The heat generated by gear teeth sliding past each other indirectly heats the lubricant eventually allowing the gear oil to again coat the gear teeth. While the friction between the gear teeth is heating the oil by frictional heating, the faces of the teeth are experiencing increased wear or even galling. If the gear lubricant thins quickly enough then only a small amount of wear will occur. If the lubricant does not quickly thin then the gear teeth may gall significantly before the lubricant begins re-coating the teeth. Galling will generate metal particles. The galling also increases the load on the gear teeth due to the reduced load carrying surface. The fine metal particles generated by metal to metal contact will be circulated by the lubricant. These metal particles will then flow back across the gear teeth and act as an abrasive under load to further increase wear.

Insufficient gear oil fluidity in cold weather operation occurs in a number of ways. One is due to crystallization of the wax in the base stock used to formulate the oil. Another is increased viscosity due to thickening of the gear oil from oxidation which is caused by excessive heat and metal debris.

Oxidation and metal debris is minimized by the choice of rust inhibitors, anti-wear and anti-oxidant components used in the oil formulation. Wax crystallization is controlled through the use of appropriate low temperature flow improvers which are also called pour point depressants. Low temperature flow improvers function by disrupting the growth of wax crystals, thus preventing formation of a strong crystal matrix. Choosing the appropriate low temperature flow improver and treat rate is critical to keeping wax crystals from forming a strong crystal lattice matrix. A strong matrix prevents the gear oil from flowing to the gears as they move. This effectively allows the gears to cut channels in the lubricant leaving little or no oil on the gear teeth. A gear oil that doesn't flow due to wax crystallization can exhibit properties similar to those of a gel while having a viscosity well within specifications. When a gear oil gels, it may need to reach a much higher temperature before the gel weakens to allow flow.

To ensure a gear lubricant will have adequate fluidity at low temperatures, the SAE J306 gear oil specification has low temperature viscometric limits. These are measured by the ASTM D2983 Standard Test Method for Low Temperature Viscosity of Lubricants by Brookfield Viscometer which was first published as an ASTM standard in 1971.

Although ASTM D2983 has been in use for close to forty years, it was not the first test to measure gear oil fluidity. Prior to D2983, specifications used the 'Channel Test' to assess low temperature fluidity. This test, FTM 792-3426, is still cited in the Mil-PRF-2105E gear oil specification.

The Channel Test is accomplished by placing a 650 mL lubricant sample in a special container. This sample is preheated to 46 ˚C before placing it in a thermostatically controlled bath which is at the final test temperature. It is left in the bath for 16 hours. At the completion of the 16 hour soak, a spatula is drawn through the lubricant cutting a 2 cm wide channel. The time for the lubricant to flow back into the channel is timed. Current specifications call for the channel to fill in less than 10 s.

Table 1 – SAE J306 Viscosity Classification for Automotive Gear Oils

SAE Viscosity Grade	Maximum Temperature for a Viscosity of 150,000 mPa(s) by ASTM D2983, ˚C	Minimum Viscosity at mm^2/s (cSt) at 100 ˚C by ASTM D445
70W	-55	4.1
75W	-40	4.1
80W	-26	7.0

90W	-12	11.0

When gear oil specifications cite ASTM D2983 for low temperature viscosity, they cite the maximum temperature for a viscosity of 150,000 mPa(s). These limits are shown in Table 1. ASTM D2983 was accepted as a replacement for the Channel Test due in part to it being more precise and a less subjective assessment of low temperature viscosity.

Similar to the Channel Test in many ways, ASTM D2983 is an overnight test. In this test, a tube containing lubricant is heated to 50 ˚C for 30 minutes then allowed to cool to room temperature. After reaching room temperature, the sample tube with the rotor in place is typically placed in a refrigerated air chamber that is at the test temperature. After a 16 hour soak the sample tube is placed in a pre-chilled insulated holder and removed from the air chamber to measure the viscosity with a rotational viscometer which is typically located on a nearby lab bench. The operator seeks to quickly measure the viscosity to minimize the samples' temperature rise from the soak temperature. A typical low temperature thermostatic air chamber is about the size of a chest type home freezer but with forced air circulation.

There are several steps in the D2983 test procedure where inconsistencies in conducting the test can result in large variations of test results or measurement uncertainty. Some of these issues are: Actual length and temperature of sample pre-heat, variation in time between removing the sample from the air chamber to finishing the viscosity measurement, and disruption of any wax structure in the sample when connecting the viscometer spindle. There are other aspects of the procedure which can contribute to variation in test results.

A few years ago ASTM D6821 was developed as an alternative to ASTM D2983. This test utilizes the same Mini-Rotary Viscometer that is used in ASTM D4684 (required for meeting the SAE J300 specification for engine oils) with a few operational changes. The differences in configuration are D6821 uses a special set of rotors and a different weight set. D6821 thermal conditioning program mimics the sample heating and cooling defined by D2983. ASTM D6821 is titled Standard Test Method for Low Temperature Viscosity of Drive Line Lubricants in a Constant Shear Stress Viscometer.

D6821 was developed by D. L. Alexander with support from Cannon Instrument Company. The development of this test is discussed in SAE paper 1999-01-3672. In summary, for D6821 a measured sample is placed in one of the test cells of a Mini-Rotary Viscometer (CMRV). After the instrument preparation is complete, a temperature program is initiated which warms the sample to 50 ˚C and holds it there for the required time. The sample is then cooled to room temperature. After reaching room temperature it is cooled at a rate similar to the air bath used in D2983. After 16 hours, the yield stress and viscosity are measured with the data automatically recorded by the instrument.

ASTM D6821 provides several advantages over D2983 which are: A smaller sample size of 10 mL, automatic thermal conditioning of the sample, and it provides two rheological properties without unnecessarily disturbing the sample. Since the CMRV is a constant stress viscometer, both yield stress and viscosity can be measured. It is believed that these advantages are why ASTM D6821 is a more precise viscosity measurement technique. A comparison of the two methods precision is shown in Table 2 at the specification limit. The precision of D2983-04 is a power function so percent repeatability and reproducibility varies with measured viscosity. The precision of D6821 is a constant over the viscosity range of the test method and not effected by the magnitude of the viscosity measured.

Table 2 – Viscosity Measurement Precision for 150,000 mPa(s)		
Test Method	Repeatability, %	Reproducibility, %
D2983	12.7	37.8
D6821	10.3	17.2

The ability to measure yield stress provides another assessment of structure formation that is only visible in the Channel Test. The presence of yield stress is an indication that the sample is not slumping to fill the channel. This is a different phenomenon than seen when a lubricant has an excessively high viscosity. This lack of slumping indicates to a user that the oil has formed a gel like structure. If this structure is strong enough it will interfere with or prevent lubricant flow around the gear teeth. A high yield stress indicates the tendency of a formulation not to slump. Yield stress cannot be measured with D2983.

The SAE paper by Alexander, et al, demonstrated the value of the D6821 technique for gear oils. Although the precision study was on a limited number of samples, those data showed excellent precision as well as correlation with ASTM D2983. Over the last several years, Cannon Instrument Company has conducted measurements on a number of commercial samples to again demonstrate D6821 test precision. This data set also includes comparisons to D2983 data. For this study the D6821 data was collected using two MRV instruments – the Cannon models CMRV-4500 and CMRV-5000.

Several commercial gear oil samples were obtained over a period of time from local resellers. The sample set also includes a sample from the ASTM Committee D02 ILCP cross-check program for gear oils.

The following provides a comparison of the viscosity data collected on the commercial samples. In this study, each sample was tested at least twice in each CMRV instrument. An accredited commercial laboratory provided the comparative D2983 viscosity data on the commercial oil samples was obtained. For the ASTM ILCP sample, the average D2983 viscosity from the test report was used as the reference value.

Table 3 – 75W Multi-grade Gear Oils at -40 °C				
Sample	Grade	Average Viscosity,	D6821 Average % Variation	D6821 vs D2983, %

		mPa(s)		
8G9	75W-140	150807	8.7	<2.7
39C	75W-140	129602	4.6	>2.1
957	75W-90	161204	0.1	>30.1
C40	75W-90	81276	4.5	<5.6
49C	75W-90	74876	5.3	<4.2
G14	75W-90	92700	7.7	<3.4

Table 3 shows the average of eight D6821 measurement variations for the 75W multi-grade gear oil. Using D6821, these measurements had an average overall variation of 5.2%. This corresponds to an ASTM reproducibility of approximately 12% which is well within the precision stated in D6821 and a third of D2983 precision. With the exception of sample 957, D6821 viscosity data is essentially identical to that obtained with D2983. Sample 957 had a high yield stress, greater than 34 Pa while the yield stress for the other samples was 11.3 Pa or less. Since there is good agreement between the D6821 and D2983 for the other samples, the difference seen with sample 957 is likely due to the presence of yield stress (or gel-like structure).

Table 4 – 80W Multi-grade Gear Oils at -26 °C				
Sample	Grade	Average Viscosity, mPa(s)	D6821 Average % Variation	D6821 vs D2983, %
GO1008	80W-xxx	101850	5.3	< 8.8*
GO1012	80W-xxx	112630	0.7	<7.7*
411	80W-140	56699	1.2	> 2.1
585	80W-90	122209	3.9	> 27
92C	80W-90	93506	7.9	< 32
239	80W-90	66167	4.4	< 0.2
119	80W-90	62401	2.9	< 9.2

*The reference D2983 viscosity is from the ILCP report.

The variance in D6821 viscosity measurement for the 80W and 85W multi-grade gear oils is shown in Tables 4 and 5. The overall average variation for each grade is 3.8 and 5.3 % respectively. This average variance is very similar to that seen in Table 3 for 75W multi-grade oils. These variances when converted to ASTM reproducibility are within the precision stated in ASTM D6821 and a third smaller than the precision stated in D2983.

In Table 4 there are two samples that show significantly different viscosities between D6821 and D2983 measurements. Sample 585 exhibits a D6821 viscosity that is greater than the D2983 measurement by more than 27%. However the D6821 viscosity for sample 92C is less than D2983 value by nearly an identical amount (32%). While in Table 5, the D2983 viscosity of samples 575 and 104 are both significantly less than the D6821 viscosity.

Table 5 – 85W-xxx Gear Oils at -12 °C				
Sample	Grade	Average Viscosity, mPa(s)	D6821 Average % Variation	D6821 vs D2983, %
MC1	85W-140	138998	5.9	> 4.8
PB2	85W-140	133190	7.1	> 8.8
575	85W-140	104614	5.4	> 29.3
104	85W-140	51830	3	> 25.2

In each case where there is a large difference between viscosities measured by D6821 and D2983 the difference between the methods is very similar - approximately 30%. In three cases D6821 measures an apparent viscosity which is greater than D2983, while in two cases the reverse is true. Out of the seventeen samples there were five samples with a significant difference in viscosity between the two test procedures.

Without a channel test to evaluate the slump rate, judging the effects of measured yield stress on the fluids ability to slump is difficult. It is known from the earlier studies on engine lubricants that yield stress and high viscosity aren't dependent variables until you approach the solidification temperature. In this set of data, only sample 957 exhibited the largest yield stress which was greater than 34 Pa. For this particular sample, the viscosities measured by these two methods were significantly different. Only one other sample, PB2, consistently exhibited a yield stress greater than 11.3 Pa, the lower limit of detection for D6821.

It is likely that the large viscosity differences seen in five samples are at least partially due to differences in base stock wax type. Contributing to these differences could also be the low temperature flow improver used, additive component interaction or even additive solubility.

With respect to wax, the current preheat requirement was added to ASTM D2983 in the mid 1980's. This work was initiated by an automotive gear oil marketer. They discovered that some formulations without preheating had an exceptionally high variance in D2983 viscosity. After further study, they found that this occurred when the base stock contained significant amounts of micro crystalline wax. By adding a 50 ˚C preheat, they reduced the variability in D2983 viscosity measurements on gear oil samples containing micro crystalline wax. The reduced variability was sufficient to bring those results within D2983 precision. This change did not have any impact on results of gear oils not containing micro crystalline wax. This emphasized the importance of ensuring all wax is in solution prior to cooling the sample in preparation for viscosity measurement.

The 50 ˚C preheat is effective because it is warm enough to bring the base stock wax into solution but not high enough to cause a change in the gear lubricants additive chemistry.   Without the sufficient preheat, there are variable amounts of suspended crystallized base stock wax in the test sample. These wax crystals will act as nucleation sites for the wax in solution as the sample is cooled. The additional nucleation sites reduce the effectiveness of the low temperature flow improver increasing the variability in low temperature viscosity. Using D6821 provides a consistent sample preheat both in terms of temperature and time, that is difficult to achieve with D2983.

Poor low temperature flow of automotive gear oils is not likely the sole reason the gears in a transmission case or gear box fail. Poor fluidity that results in poor lubrication will definitely contribute to a shorter useful life, or catastrophic failure in a critical situation. ASTM D6821 can help avoid poor fluidity situations because of its ability to indicate whether a formulation has a tendency to gel.

In summary, ASTM D6821 provides a more precise viscosity measurement than ASTM D2983. This significantly better precision is due in large part to consistent preparation of the sample and viscosity measurement. It also eliminates the numerous sample handling steps of D2983 that can contribute to variable test data. Additionally, the use of D6821 not only improves the reliability of the test results, it also reduces the amount of technician time required to complete the test. By improving the precision of the test, formulators will gain additional latitude in choosing components that deliver the required performance for their gear oil blends.

The industry would benefit by the addition of ASTM D6821 to the Committee D02 ILCP Gear Oil program. This would provide the industry with a broader sample base for comparing the capabilities of these two methods.

Authors background:
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For more information regarding this article and ASTM D6821, please email Cannon Instrument Company at cannon@cannoninstrument.com or visit

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