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The Impact of SAE Critical Specifications to the formulating and manufacture of automotive oils

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Viscosity as a concept will be familiar to everyone. People talk of liquids as either being “thick” like treacle or “thin” like water though, more properly these should be described as being viscous and fluid respectively.

When it comes to lubrication, the viscosity of fluid that is employed to keep moving surfaces apart is probably the most important consideration if wear or excessive losses due to friction are to be avoided.

There are a very wide range of applications for internal combustion engines from cars and trucks, through to powering boats and trains and providing back-up electrical power for critical installations. However, fortunately, in almost all applications the viscosity of the engine lubricant is defined by a single, globally accepted, document known as the J300 standard published in the USA by the Society of Automotive Engineers (SAE).

This standard sets limits for two series of viscosity grades; those containing the letter W and those without. These are sometimes known as “winter” and “summer” grades which, although a useful distinction, is not completely technical correct.

Viscosity grades such as SAE 10W-40 and 5W-30 and the like will be familiar to anyone who buys oil for their car but what might not be so well known is that there are actually four viscosity tests which are used to define the range of grades. What may come as a surprise to many people is that three of these tests are described by the SAE as being “critical” specifications. This paper aims to explain the significance of critical specifications and the potential impact on formulators, manufacturers and users.

The four viscosity tests that are employed in the SAE J300 standard can categorised by the testing temperature and the degree of shearing to which the oil is subjected during the test. They can be represented as a grid – see Fig. 1.

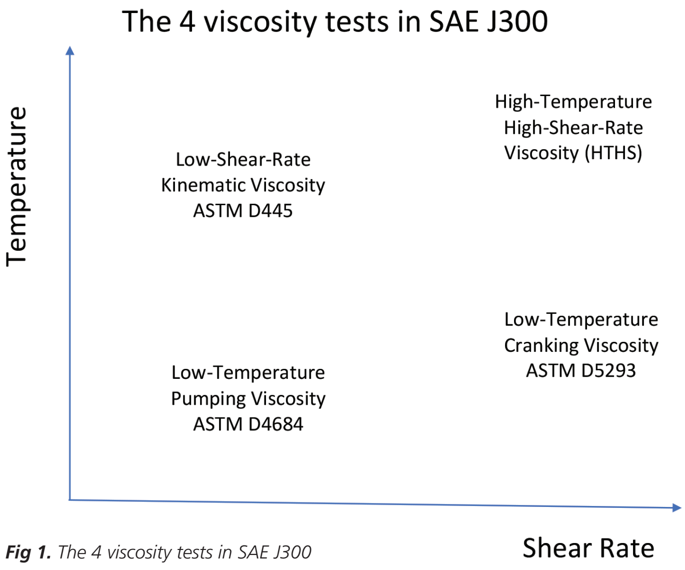

***Fig 1.** The 4 viscosity tests in SAE J300*

Perhaps a few words on each of the four tests would be useful.

Two low-temperature tests are employed to define the limits of “W” grades.

The first, **low-temperature cranking viscosity** is measured by ASTM D5293 and has been found to correlate with the ability of an engine to start at low temperatures. The test is run at temperatures between -10°C and -35°C and subjects the oil to a high rate of shearing during testing.

Low-temperature pumping viscosity (ASTM D4684) cools the oil to an even greater degree (-15°C to -40°C) over an extended period of time, designed to allow any wax in the oil to crystalize. Such waxy materials can produce a gel preventing the oil flowing into the oil pump and hence lead to oil starvation in the early stages of operation in winter conditions before the engine and the oil warm up.

Then there are the two high-temperature tests which mainly apply to the grades which don't contain the letter "W" and are often used on their own to describe monograde lubricants i.e. those that contain no viscosity index improver.

The simplest of these tests is **kinematic viscosity** which is run at 100°C by ASTM D445 and measures the rate of flow of the oil under the influence of gravity. Most oil laboratories, even the most rudimentary, will run this test which is also used for transmission fluids and, with modifications, industrial oils as well. However, its simplicity is probably its most attractive feature as in a real engine situation the only time when the oil is flowing under gravity at a temperature around 100°C is when it is draining back to the sump, and this is hardly the most stressful of its operations.

Of significantly more importance is the other high-temperature test known as the **high-temperature high-shear-rate (HTHS) viscosity**. This is measured by a number of different methods but all at 150°C which is a more realistic figure for the working parts of an engine and subjects the oil to the sort of high shear rates which are likely to be found in critical parts such as the bearings and between piston rings and cylinder walls under severe operating conditions.

The HTHS viscosity is an extremely important parameter to the engine designer. Too low a figure and the oil will not keep moving metal surfaces apart which can lead to very high rates of wear and early engine failure. Too high a value will result in the efficiency of the engine, and hence the fuel economy, being reduced. Much of the recent improvements in fuel economy have come about due to the development of special oils with low HTHS values.

Taken together these tests completely define products in the SAE J300 standard which is shown in Table 1.

Up to now, nothing has been said about the Critical Specifications mentioned in the title of this paper. So, what are they? They are defined as being specifications which due to some aspect of the product characteristic or end-use of the product, or both, require that the user has a high degree of assurance that the true value of the product property actually meets, or exceeds, the quality level indicated by the specification limit value.

SAE Viscosity Grade	Low-Temperature Cranking Viscosity (CCS)	Low-Temperature Pumping Viscosity (MRV)	Low-Shear-Rate Kinematic Viscosity (KV100) at 100 °C		High-Shear-Rate Viscosity (HTHS) at 150 °C
	ASTM D5293	ASTM D4684	ASTM D445		Various methods
	mPa.s (max)	mPa.s (max)	mm^2/s (min)	mm^2/s (max)	mPa.s (min)
0W	6200 @ -35 °C	60000 @ -40 °C	3.8	-	-
5W	6600 @ -30 °C	60000 @ -35 °C	3.8	-	-
10W	7000 @ -25 °C	60000 @ -30 °C	4.1	-	-
15W	7000 @ -20 °C	60000 @ -25 °C	5.6	-	-
20W	9500 @ -15 °C	60000 @ -20 °C	5.6	-	-
25W	13000 @ -10 °C	60000 @ -15 °C	9.3	-	-
8	-	-	4.0	< 6.1	1.7
12	-	-	5.0	< 7.1	2.0
16	-	-	6.1	< 8.2	2.3
20	-	-	6.9	< 9.3	2.6
30	-	-	9.3	< 12.5	2.9
40	-	-	12.5	< 16.3	3.5 (0W, 5W, 10W)
40	-	-	12.5	< 16.3	3.7 (other grades)
50	-	-	16.3	< 21.9	3.7
60	-	-	21.9	< 26.1	3.7

***Table 1.** The SAE J300 Standard for Automotive Engine Oils*

So, what does this mean in practice?

Let's take the case of a blender making a SAE 30 oil. This should have a kinematic viscosity at 100°C measured by ASTM D445 of between 9.3 and 12.5 mm^2/s. Suppose the blender tests the product and gets a result of just above the specification minimum, say 9.301 mm^2/s.

Now the blender could argue that the product met the specification and therefore release it for sale. But, kinematic viscosity is defined in the SAE J300 as being a critical specification so there should be a high degree of assurance that the true value is within specification. Generally, the high degree of assurance equates to a 95% confidence level or being right 19 times out of 20.

Even if the blender's equipment for measuring viscosity is perfectly calibrated and exhibits no bias there will always be some imprecision in the test results. For a Critical Specification the blender should only release the material if the result obtained is far enough inside the specification to take into account this inherent variation. This more conservative value is known as the Acceptance Limit.

The SAE J300 standard directs the reader towards another standard (ASTM D3244) when it comes to dealing with these issues and how far from the Specification Limit the Acceptance Limit lies. Basically they can be very close together for laboratory tests which have a high degree of precision. Fortunately kinematic viscosity by D445 is such a test and whereas the Specification Limits for a SAE 30 oil are 9.3 to 12.5mm^2/s, the Acceptance Limits are 9.376 to 12.40mm^2/s.

In practice a blender is unlikely to release a batch of material that is really close to the specification limit because it allows no tolerance for the viscosity to change as a result of the packaging process. In the case of kinematic viscosity, as the Acceptance and Specification Limits are close together, the fact that this is a critical parameter is not likely to be a significant problem. However, in the case of other SAE J300 tests this is far from the case, as we shall see later.

For the sake of completeness, it is necessary to see how these Acceptance Limits are calculated. ASTM D3244 describes the process in detail and also gives a methodology for resolving disputes between a supplier and receiver who have both tested the same material and obtained differing results. However, in the case of a blender deciding whether they should or should not release product on a single test result the following equations apply.

For a maximum specification:
Acceptance Limit = S - 0.594* R where S is the specification limit and R is the published reproducibility of the test method.

Similarly, for a minimum specification:
Acceptance Limit = S + 0.594* R
These equations are both for 95% confidence limits.

Using these equations, a table can be built to show both Specification and Acceptance Limits for SAE J300 kinematic viscosity – see Table 2.

As can be seen from Table 2, the difference between Specification and Acceptance Limits for kinematic viscosity tested by ASTM D445 is quite small due the extremely high precision associated with this test method. Unfortunately, the same cannot be said for the other tests referred to in the SAE J300 standard. These will now be examined in turn.

Low-Temperature Pumping Viscosity by ASTM D4684

Although the SAE J300 standard specifies that just one method (ASTM D4684) shall be used to determine this critical parameter there is a slight complication in that it allows 2 separate procedures and these have different published levels of precision. In this paper only the more recent Procedure A will be considered as this employs more modern cooling techniques, as well as removing the need for using methanol as a heat transfer medium with all its associated toxicity issues.

SAE Viscosity Grade	Specification Limit		Acceptance Limit	
	mm^2/s (min)	mm^2/s (max)	mm^2/s (min)	mm^2/s (max)
16	6.1	< 8.2	6.150	8.133
20	6.9	< 9.3	6.957	9.224
30	9.3	< 12.5	9.376	12.40
40	12.5	< 16.3	12.60	16.17
50	16.3	< 21.9	16.43	21.72
60	21.9	< 26.1	22.08	25.89

Table 2. *ASTM D445 Kinematic Viscosity Acceptance Limits for unused engine oils – based on single test*

Procedure A has the additional advantage that the published precision data is not temperature dependent so the same figure can be used for any grade from 0W-xx to 15W-xx oils, which were the only grades used in the precision study.

Around the maximum specification limit of 60,000 mPa.s the published reproducibility is 14.6% of the mean result for unused oils.
Using the expression quoted above:
Acceptance Limit = S - 0.594* R
= 60000 – 0.594* 8760
= 54800 mPa.s

Therefore, the blender should not release the product if, when a single sample of the material is tested, a result for low-temperature pumping viscosity of greater than 54800 mPa.s is obtained.

For the record, the precision of Procedure B was not quite as good as Procedure A when 10W-xx and 15W-xx oils were evaluated and significantly worse when 5W-xx and 0W-xx oils were studied. This implies that anyone using this procedure on older test instruments should not release blends unless they are significantly further within the specification limits.

High-temperature high-shear-rate (HTHS) viscosity

Switching to the other high-temperature test, that of HTHS viscosity, there is a further complication in that there is more than one method allowed in the SAE J300 to determine this critical parameter and they do not share common levels of precision.

For this paper only ASTM D4683 which employs the commonly used Tapered Bearing Simulator Viscometer will be considered.

Specification Limit	Reproducibility	Acceptance Limit
mPa.s (min)	mPa.s	mPa.s (min)
2.3	0.113	2.37
2.6	0.122	2.67
2.9	0.132	2.98
3.5	0.151	3.59
3.7	0.158	3.79

Table 3. *Specification and Acceptance limits for HTHS viscosity by ASTM D4683*

While the precision of this test method is not temperature dependent, differing values are reported for each of the HTHS viscosity limits shown in the SAE J300 standard. From these results the acceptance limits for HTHS viscosity have been calculated and are shown in Table 3 together with the SAE J300 specification limits.

Acceptance limit values have been quoted to the nearest 0.01 mPa.s as this is the protocol required by the test method. However, it should be noted that in the SAE J300 standard (as well as other automotive standards such as the ACEA sequences) the minimum values for HTHS viscosity are shown to only 1 decimal place. This difference is a likely source for interpretation by both formulators and any blender that has the capability of measuring HTHS viscosity, particularly given the importance of this parameter in meeting fuel economy targets.

Low-temperature Cranking Viscosity by ASTM D5293 – Cold Cranking Simulator (CCS)

This test is different from those that have been discussed already in that it is deemed to be a non-critical specification in the SAE J300 standard.

A non-critical specification is defined as one that requires assurance only that the product property is not significantly poorer than the specification limit.

With non-critical specifications the supplier can blend up to, but not exceeding, the specification maximum. They should not release the product if it is in excess of the specification maximum no matter how close it is to the limit.

If the customer tests the product and obtains a fail versus the specification limit but it is less than the acceptance limit derived from test reproducibility, there is no cause to reject the product.
ASTM D5293 has two procedures but for the sake of simplicity only the modern thermoelectric cooling systems will be considered.

SAE Viscosity Grade	Specification Limit	Acceptance Limit
	mPa.s (max)	mPa.s (max)
0W	6200	6420
5W	6600	6840
10W	7000	7250
15W	7000	7250

Table 4. *Specification and Acceptance Limits for Low-temperature cranking viscosity by ASTM D5293*

Although the precision using this procedure is not temperature dependent, the specification limits do change with temperature and hence the acceptance limits track them. This being a non-critical specification, the test uncertainty adds to the specification maximum to give a higher acceptance limit.

The Specification and Acceptance limits for oils covered by this method are shown in Table 4.

If the customer receives product that fails his test for cold cranking viscosity, he is entitled to check with the supplier that the product passed before being released, this being a requirement of the SAE J300 standard.

In the event that the supplier and customer cannot reach an agreement then additional testing should be undertaken on the same material, which will have the effect of reducing the statistical uncertainty and establishing a better "true" value for the parameter under consideration.

A word on gear oils

In the same way that SAE J300 describes the viscometric requirements of automotive engine oils, there is a similar standard – SAE J306 – which deals with automotive (manual) gear oils.

SAE Viscosity Grade	Maximum temperature for Viscosity of 150,000 mPa.s by Brookfield viscometer	Kinematic Viscosity at 100 °C (KV100)	
	ASTM D2983	ASTM D445	
	°C	mm^2/s (min)	mm^2/s (max)
70W	-55	4.1	-
75W	-40	4.1	-
80W	-26	7.0	-
85W	-12	11.0	-
80	-	7.0	< 11.0
85	-	11.0	< 13.5
90	-	13.5	< 18.5
110	-	18.5	< 24.0
140	-	24.0	< 32.5
190	-	32.5	< 41.0
250	-	41.0	-

Table 5. *The SAE J306 Standard for Automotive Gear Oils*

This has just two tests, high-temperature kinematic viscosity again using ASTM D445 and low-temperature viscosity using a Brookfield viscometer. Both of these are designated as being critical specifications. Table 5 shows the allowed SAE grades and their respective limits.

The kinematic viscosity specification limits are quite wide and as ASTM D445 is a very precise test the Acceptance Limits are close to the Specification Limits and should not cause a significant problem for formulators or blenders. However, there is a separate issue with the kinematic viscosity of gear oils in that J306 states that they should still meet the kinematic viscosity limits after the product has been subjected to very high levels of shear in a test that lasts for 20 hours. In practice this only really impacts 75W-90 gear oils but means that they have to be manufactured with very shear resistant viscosity index (VI) improvers often based on polyalkyl methacrylate (PAMA). Using the sort of VI Improvers usually found in engine oils will result in gear oils that fail to meet this SAE J306 requirement.

If the ASTM D445 test for kinematic viscosity can be described as having high levels of precision the same cannot be said of the other test required by the J306 standard, that of low-temperature viscosity using the Brookfield method ASTM D2983.

In this test the specification limit is the same across all grades and is set at 150,000 mPa.s maximum. However, the test temperature varies from a modest -12°C for a 85W grade down to -55°C for a 70W product.

Taking the case of the increasingly popular 75W-90 gear oil, this has to be tested at -40°C and at this temperature the reproducibility of the test using a liquid bath to do the cooling is 28.5%. Calculating the Acceptance Limit produces a figure just under 125,000 mPa.s which is quite a long way from the already challenging specification of 150,000 mPa.s.

Summary

Although the SAE standards for the viscosity limits of automotive engine and gear oils are universally accepted within the industry, some of their features appear to be less widely known. In particular the concept of critical specifications and the more stringent acceptance limits that go with them may be new to a number of readers.

Formulators need to work within the acceptance limits if their customers, the blenders, are to have any chance of meeting their obligations when new products are placed on the market.

Similarly, blenders should avoid the temptation to alter formulations in an attempt to reduce costs if this means that products will fall the wrong side of these more demanding limits.

An understanding of these requirements should bring about an improvement in lubricant product quality and hopefully this short paper will have at least gone some way to raise awareness amongst readers.

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Following a period of research at Cambridge, Ted joined the Esso Research Centre and was responsible for electron microscopy and all aspects of elemental analysis.

Moving into lubricants his positions within Esso included quality control, marketing and procurement. For a number of years he was on assignment as Technical Manager at Comma Oil. Ted is still very much involved in the lubricants industry, especially with training, and consults on problem solving. He also serves on the Technical Review Panel of the VLS scheme.