

Demystifying lubrication



John Coxon of Independent Powertrain Projects demystifies lubricants for racing engines

Without doubt the most technically complex component in any race engine is the lubricating oil yet invariably it is the component your average engine designer, development engineer, even, dare I say it, Chief Engineer knows the least about. Over the years millions of man hours have been expended in the effort to develop the perfect lubricant and tremendous advances have been made but to the user, 'Well it's just oil isn't it?' as an industry colleague put it to me the other day.

Having been involved in lubricant and engine lubrication issues over the greater part of my working life I have often wondered how people who although very knowledgeable about other automotive issues, make decisions on something as complex as a modern day engine lubricant when up to date knowledge of the subject is so very hard to find. As if the current situation is not confusing enough new specifications being launched into the European market in 2005 will add an extra dimension to that selection process.

In highlighting this general lack of understanding, I am not apportioning blame to any particular group. In order to describe the properties and characteristics of lubricants engineers and chemists have had to assign certain terms that, until one has a reasonable understanding, makes further progress difficult. It is also fair to say that sometimes the lube industry doesn't go out of its way to explain things very well and sometimes uses this mystique to baffle the customer.

A number of very good books have been written on the subject. They, however, tend to be very thorough and it can be difficult for your average technocrat to wade through the early chapters, which lead to the more interesting areas.

In this article I will describe what I believe to be the important aspects to the engineer/racer. I will try to blow away some of the 'mystique' so that you can start quizzing your lube supplier a little more closely and get answers relevant to you. I do not apologise for going back to basic lubricant definitions because this, in my opinion is where much confusion starts and where some of the oil companies try to exploit the confusion to their benefit.

TYPES OF OIL

The first of these misrepresentations is the synthetic/ semi synthetic/ part synthetic /mineral basestock discussion.

If we start right at the beginning, any engine oil consists primarily of two main classes of component: the base oil and the additive package. The base oil provides the bulk of the

product (perhaps 75 - 85% of the total) and gives the end product much of its properties in terms of viscosity and thermal stability. The additive pack, which by simple arithmetic can constitute 15 - 25%, is there to modify the base oil properties in order to give the finished oil those properties more desirable in an internal combustion engine or to extend the life of those properties.

Today, the majority of base engine lube oils are still derived directly from a barrel of crude oil. In the past some oils, those mainly used for racing could have been derived from vegetable oils (more on this later) and in the future we may be seeing so-called GTL (or Gas-to-Liquid) oils as we try to find more and more uses for natural gas in addition to just burning it. For the time being, however, we can comfortably say that the majority of what you see in the market place is derived from your basic barrel of crude.

The first stage of the refinery process is when the crude oil is heated to 350 deg C and sent through the initial atmospheric distillation plant, separating out the shorter chain molecules which can be subsequently blended into fuels (propanes, gasoline, kerosene, gas oil, etc.). The residue of this process, (i.e. anything that does not boil off including those longer chain molecules that could be thermally 'cracked' or broken down by the heating process at atmospheric pressure) is then subject to a vacuum distillation at around 400 deg C which generates the different types or 'fractions' of base lubrication oil, depending the initial composition of the crude.

These different 'fractions' can be further refined in processes such as solvent extraction (to remove aromatics and some naphthenes), hydrofinishing (to convert the remaining unstable compounds to more stable versions) and solvent dewaxing (to remove wax and improve the low temperature properties of the eventual oil). For some of these fractions (Group III see below), further refining may be necessary such as hydrocracking. This can convert a heavy feedstock into a much superior base oil as it breaks down the long molecular chains into products that are more stable with good viscosity characteristics.

Table One

Group	Saturates	Sulphur content (%)	Viscosity Index(VI)
I	<90%	>0.03%	80-120
II	>90%	<0.03%	80-120
III	>90%	<0.03%	120+
IV	Polyalphaolefins	n/a	n/a
V	All others		

Thus as in Table One we have a number of types or groups of oil (Groups I to III) which have been derived from traditional refining of crude oil. These are categorised essentially by their degree of refining (the percentage of saturated hydrocarbon chains), the amount of sulphur in the basestock product (sulphur is undesirable for the most part in lube basestocks) ➤

and the Viscosity Index (see sidebar for an explanation of this).

It should be noted that increasing the amount of saturated hydrocarbons in the basestock improves the quality or stability of the product. These oils are all still in effect a very wide range of naturally occurring compounds of differing chemical composition. Some other mineral basestock types (eg naphthenes) derived during refining come under Group V but these are of lesser importance in the motorsport environment.

Also in the table are Group IV and V oils. These are those oils that have been made by means other than traditional refining they and are often referred to as 'synthetic' basestock oils.

Here is the nub of much confusion. Although Polyalphaolefin based oils were originally discovered in the 1930s it was not until the 1970s that Mobil began marketing them under the Mobil SHC (Synthetic Hydrocarbon) brand at vastly increased price over the other mineral based products available in the marketplace. Later on, a marketing campaign in Germany was

National Advertising Division for the Council for Better Business Bureau: 'Any process beyond physical separation can result in a synthetic product'. It would seem that the term 'synthetic' in the context of lubrication, is deemed to describe an oil of higher performance and not necessarily the basestock availability. This however applies only in the US!

In Germany synthetic products are ruled as those containing POA. Hence the confusion...

For my part, in my time at a major OEM I tried to delete the word 'synthetic' from the corporate vocabulary preferring to refer only to oils by their specification (ACEA A3, etc,) or category (Group I or III, etc,). I would advise you to do the same.

Make no mistake, some Group III basestocks are very good and in some cases are approaching levels of performance of some of the Group IV stuff, so why hide it?

In reality the game will be given away by the price. To my knowledge the cost of producing PAO blends is much greater

“So forget the terms synthetic, semi-synthetic or part synthetic and ask about performance specification or category of basestock”

able to differentiate synthetic oil products in the eyes of the consumer and thus a very lucrative section of the lube oil market had been produced.

Instead of the more normal route of refining, these oils had been produced by the chemical process of taking smaller hydrocarbon chain molecules produced elsewhere in the petrochemical industry (for instance ethylene, C_2H_4) and reacting them together to give longer chains. The process consequently generates highly paraffinic, low volatility oils with high viscosity indices giving improved resistance to oxidation and better thermal stability. By selecting the most appropriate of these we can also produce oils with more desirable viscosity/temperature characteristics, superior volatility (and hence reduced oil consumption), better frictional properties and (albeit not one particularly important for motorsport activities), better cold flow performance.

The success of these products in the German market place didn't go unnoticed but the term 'synthetic' was not well defined. Other oil manufacturers, keen to advertise their products in a better light adopted the term claiming that their oil (a Group II or III product) was superior to the base mineral products.

This was inevitably tested in the US legal system, which eventually in April 1999 came up with a ruling in the (US)

than the highly refined Group III and unless the oil manufacturer is totally unscrupulous this will be reflected in the eventual price. So forget the terms synthetic, semi-synthetic or part synthetic and ask about the performance specification or category of basestock.

I must add at this point that for the impecunious racer on a very tight budget there is often little wrong with using Group I mineral oil provided you do not step outside its capabilities. In most cases this will mean fully warming up the engine prior to the event and ensuring that the oil temperature is kept within reasonable bounds by adequate cooling. I have in the past run for a whole season or more on a mineral 15W/50 without any adverse effects and no damage to the engine found at the end of season strip.

While I may have given the impression that POA oils are superior in every way to refined mineral blends, this is not necessarily the case. In the case of crankshaft or camshaft oil seals (if fitted), these are normally made from fluoroelastomers or PTFE and in the presence of lubricants will absorb some of the oil and consequently swell. This swelling is beneficial and improves the sealing characteristics ensuring no leaks around the crankshaft near the front pulley or in the inaccessible position of behind the flywheel.

This swelling is normally an entirely reversible reaction and

when the oil is taken away the seal will shrink again. Group I oils exhibit this characteristic in abundance and will cause the seal to swell ensuring no oil leaks. Group III oils are not so good whereas Group IV are perhaps the poorest of all in this respect.

Fortunately, however, rescue comes in the form of organic esters, which have seal swell characteristics that are quite good. Group IV basestocks are therefore blended with organic esters to mitigate the worst of these characteristics and generate oils that are less likely to see oil leaks. Composing around 10-15% of the overall oil, esters have the added benefits of being able to improve the solubility of the additives in the blend and offering good deposit control.

The final category, of which there is little on the market at the moment, is the gas to liquid technology or GTL oils. Referred to in some places as Group III+ but in Europe designated recently as Group VI, they are currently available only in Italy and are manufactured from natural gas using

the well known Fischer-Tropsch process.

This process is mainly used to cater for the increased demand for diesel fuels but it can be used to synthesize high quality lubricant basestocks on a par with some PAO products but at better economics. It is still early days but expect to see more interest in this area from the major oil companies in the future.

OIL VISCOSITY

Now that we understand a little more about the manufacture and classification of basestocks we can look further into an area where many of you will be more familiar - that of viscosity.

The viscosity of a fluid can be defined as 'the resistance of one layer of that fluid to flow over an adjacent layer'. When an oil is cold it becomes viscous and difficult to flow. When that same oil is heated it becomes less viscous and flows more readily. This change in viscosity is characterised as the Viscosity Index (VI) as described in the accompanying sidebar. ➤

VISCOSITY INDEX

The Viscosity Index (VI) is determined by comparing the change of viscosity with temperature to that of two reference oils, each having the same viscosity at 100 deg C as the test oil. One of these oils changes very little with temperature and is given a VI of 100 while the other which changes a lot is arbitrarily given the VI of 0.

Thus the Viscosity index of any oil is given by:

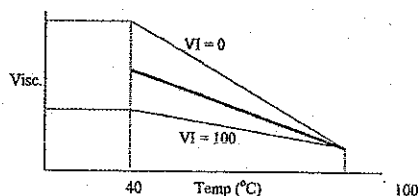
$$(VI) = 100 \times (L-U) / (L-H)$$

Where

L = the viscosity of Reference Oil VI = 0 at 40 deg C having the same viscosity at 100 deg C of the oil whose viscosity is to be calculated.

H = the viscosity of the Reference Oil
 VI = 100 at 40 deg C having the same viscosity at 100 deg C of the oil whose viscosity is to be calculated.

U = the viscosity of Base Oil at 40°C whose VI is to be calculated with the same viscosity at 100 deg C as the reference oils



For engine oils ideally we would like the viscosity to remain the same all the way up the useable temperature range but since this is never likely to be possible, current engines are designed to use very high VI oils (around 160+) ●

VEGETABLE OILS

No article on lubricants for motorsport would be complete without mentioning castor oils. Beloved by the two-stroke fraternity with its addictive aroma, as the heading suggests this oil is derived from the castor bean plant or *Ricinus communis*.

The base castor oil itself is classified as a triglyceride with a very high content (around 90%) of the fatty acid ricinoleic acid. This fatty acid has an interesting structure with a hydroxyl group that can attach itself to suitable polar groups on the surface of metal giving superior lubricity.

Having good low temperature properties, once heated this oil, unlike other oils, polymerizes to form even heavier oils, rich in esters, which are thermally even more stable and have even better lubricity!

Unfortunately the by product of all this is the formation of lacquers and varnish inside the engine and so unlike modern PAO oils, which generate very clean engines internally, castor oil ultimately produces a very dirty engine.

When left for some time, castor based oils can oxidise very readily and so traditionally it was always recommended that the engine oil was drained after use. Going back perhaps more than just a few years, I believe it was also recommended that because of deposits in the engine and the immiscibility of the oil in normal mineral oils, engine components should be scrubbed clean before changing to a more conventional oil.

Although few people use castor based oils these days, I would imagine that the detergents in modern oils would be powerful enough to remove some if not all of these deposits.

Castor oil is still marketed under the brand name of Castrol R30 (or 40) and used in two stroke mixes it still gives some of the best lubricity of all in the ring/liner zone, often in very arduous conditions. In four stroke racing engines, these oils have been largely superseded by their much cleaner PAO-based cousins and are not likely to be used in anything other than older engines. ●

Way back in the early 1900s the Society of Automotive Engineers (SAE) in North America, realising that a system of classifying viscosity was needed, came up with SAE J300. Over the years this has been changed, added to and raised to an international ISO standard. Today it is still the benchmark by which we describe engine oil viscosity.

Essentially the SAE system categorises a particular oil by its viscosity at both high and low temperature operation. The viscosities are indicated by two numbers, in the form SAE 10W/40 for modern multigrade oils. The higher the number the greater the viscosity with the first of the two numbers referring to the low temperature properties (the 'W' standing for Winter) while the other one is a guide to the viscosity at normal engine running temperatures.

Prior to the 1950/60s and before the wide scale introduction of viscosity modifiers (VM) or viscosity index improvers (VII) as they were called then, motorists would use the less viscous SAE 10W or 20W grades during the winter months and change to an SAE 30 or 40 for the summer. This was fine when oil change intervals were very short but as annual mileages rose and VM technology improved, there was an increasing demand for oils with lower changes in viscosity with temperature (higher Viscosity Index) to cover both summer and winter motoring.

Although not of great use for motorsport this did eventually lead to the development of PAO oils, which have enabled engine designers to push the envelope of tribology to higher levels.

Figure One compares the viscosity characteristics of a straight SAE 30 monograde with the latest technology SAE 0W/30 multigrade showing, for the multigrade, a lower viscosity in colder conditions (hence better cold starting) and a higher viscosity, giving better engine protection, when the engine is hot.

Viscosity Modifiers, which can be polymers (for example, polymethacrylate) or possibly co-polymers (for example, styrene-butadiene co-polymers), work on the principle that as

the temperature of the basestock increases, so does the solubility of the additive. At high temperature the long chain molecules extend into the oil and interfere with the flow thereby increasing its viscosity. At low temperatures their solubility is decreased and the long chains tend to coil into themselves, having less influence on the surrounding lubricant.

ADDITIVES

At this point the reader should have a basic grasp of what makes up around 80-90% of the product he buys. The remaining part of the oil is reserved for the additive pack. This, as its name might suggest, is a range of chemicals, which when combined into the basestock improve the oil to suit certain and perhaps specific applications. Typical additives used can be:

Anti-oxidants

These reduce the potential chemical breakdown of the lube by the action of the oxygen in the air. Without these substances the oil will age and permanently thicken with increasing temperature.

Detergents and Dispersants

As the name suggests these are added to clean the oil. The detergents hold the products of combustion that have found their way into the oil in solution. The dispersants ensure that the suspended particles do not coalesce into potentially damaging lumps. These are more important in diesel engines and perhaps less so in gasoline racing engines when oils are changed regularly.

Anti-wear additives

These are additives designed to protect under boundary lubrication regimes. The most popular compounds are those of zinc dialkyldithiophosphates (commonly referred to as ZDDP), which are not only very effective but cheap as well.

These compounds attach themselves to the metal surfaces by polar attraction very similar to the way detergents do but less so. So, in order to compete for these surfaces the concentration of these ZDDPs has to be significantly increased. Since specialist oils for competition do not necessarily need the same level of cleanliness the removal of the detergent can enhance the anti-wear properties of the oil.

Friction modifiers

In addition to the anti-wear compounds this class of additive, once considered relatively minor, is designed to reduce the friction in the boundary regime. In the past compounds designed to produce molybdenum disulphide on the metal surfaces have been used but as the total amounts of sulphur in lubricants are now being steadily reduced so organic compounds are increasingly being developed.

Figure 1

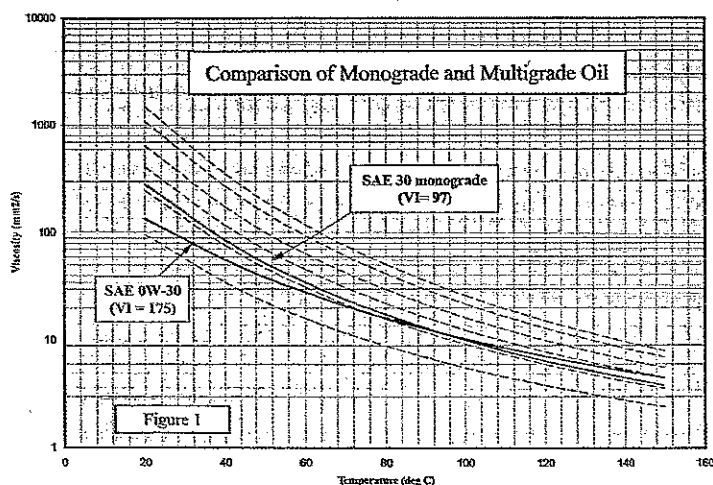


Table Two – SAE J300 viscosity grades for engine oils

SAE Viscosity Grade	Low Temp Cranking Viscosity, cP Max	Low Temp (oC) Pumping Viscosity, cP Max with no Yield Stress	Kinematic Viscosity (cSt) at 100 oC Min	Kinematic Viscosity (cSt) at 100 oC Max	High Shear Viscosity, (cP) at 150 oC and 106 s-1 Min
0W	3250 at -30	60 000 at -40	3.8	-	-
5W	3500 at -25	60 000 at -35	3.8	-	-
10W	3500 at -20	60 000 at -30	4.1	-	-
15W	3500 at -15	60 000 at -25	5.6	-	-
20W	4500 at -10	60 000 at -20	5.6	-	-
25W	6000 at -5	60 000 at -15	9.3	-	-
20	-	-	5.6	<9.3	2.6
30	-	-	9.3	<12.5	2.9
40	-	-	12.5	<16.3	2.9 (0W-40, 5W-40 and 10W-40 grades)
40	-	-	12.5	<16.3	3.7 (15W-40, 20W-40, 25W-40 and 40 grades)
50	-	-	16.3	<21.9	3.7
60	-	-	21.9	<26.1	3.7

The opposite are by no means the only additives to be used in a modern engine lubricant. Other products such as rust and corrosion inhibitors, anti-foam additives and demulsifiers can be often used depending upon the application.

As if all the above isn't enough, many of them, as I have already indicated, interact with each other and so the oil companies spend millions of pounds carefully designing their products and testing them fully before releasing to the market.

It is because of this complex interaction that I always have reservations about the use of aftermarket lube additives. While I am prepared to admit that there may be some apparent benefits to one characteristic, this may be to the detriment of some of the other properties. For example an increase in anti-wear additive may possibly only compete with the anti-wear chemistry already present in the oil and at the same time reduce the effectiveness of the detergent/dispersant.

A good quality engine oil, fully formulated for the application should be more than capable of coping with the demands of everything but the most specialist of purposes.

LUBRICATION CONSIDERATIONS FOR THE RACING ENGINE

The primary function of any lubricant is to separate moving surfaces to minimise friction and wear. As the relative velocity of the moving parts increases, a wedge of oil develops which separates the two surfaces and reduces the friction of the system. As this relative velocity increases still more, the inherent viscosity of the lubricant increases the drag and the friction increases again. This characteristic is described in the Stribeck curve as shown in Figure Two and was proposed by

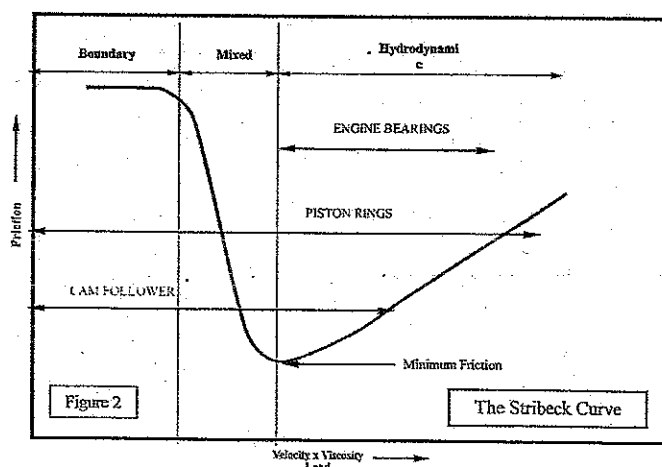
Richard Stribeck, a German professor as long ago as 1902.

At low relative velocities, the hills and valleys that describe the roughness of opposing surfaces interlock and friction is high. This is known as boundary lubrication and is the zone where most wear occurs. When the relative speed increases, the surfaces are forced apart and friction reduces rapidly to a minimum where no contact between the surfaces exists.

Since at this minimum point no contact exists no wear can take place either. Beyond this point the relative movement of the surfaces causes a wedge of lubricant to build up forcing either the surfaces to move further apart or a progressive increase in drag as a result of the viscosity of the fluid.

The creation of this 'wedge' introduces the concept of hydrodynamic lubrication and is the condition where little or no wear can take place. The band between boundary and hydrodynamic lubrication is known

Figure.2



strangely enough as mixed or transitional lubrication.

There is another type of lubrication which, for the benefit of the purist, I will mention and that is Elasto-Hydrodynamic lubrication. While the descriptions above are somewhat idealist, assuming that components are solid bodies and that lubricants are incompressible, this lubrication regime is characterized by the surfaces deforming under the increased load and the viscosity of the lubricant increasing under increased pressure and thereby supporting higher loading than the simple theory suggests.

Since this type of regime applies mainly to rolling friction (in for instance roller and ball bearings or certain types of gears) it is not relevant for my argument here but I include it for the sake of completeness.

It follows that in any design of engine or mechanical system where maximum efficiency is required, the designer should be aiming to operate at the point of minimum friction and where according to simple theory, little or no component wear will take place.

Mindful of the Stribeck curve, the three critical lubricating areas in a reciprocating engine are:

- The piston ring/ bore interface
- The valvetrain
- The main and big-end bearings

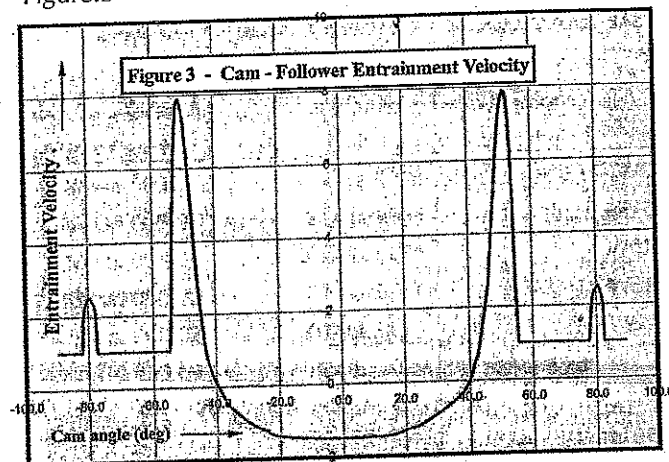
In a reciprocating engine the piston ring/ cylinder bore interface accounts for around 70 - 75% of overall friction and, by simple adoption of the above theories, a similar order of magnitude of wear. With the lubricant held in the peaks and valleys produced by the cylinder bore honing the piston ring while travelling up and down undergoes all the lubrication regimes of boundary at the top through to full hydrodynamic at mid bore to boundary once again at the bottom of the stroke. While piston ring side loading at this position is low, at the top of the stroke and on the firing cycle, this side loading is not only very high but at a point where only boundary lubrication can apply (that is, velocity = 0).

In older engines we can therefore often see a 'step' in the bore at the top ring reversal point at this position of maximum friction and hence cylinder bore wear. This wear, particularly in racing engines, can be reduced by the adoption of soft piston rings which give the added benefit of quicker bedding in. However, without any additional formulation, base lubricants would be incapable of protecting the running surfaces at this position.

Likewise in the valvetrain, the tribology of the cam and follower interface will run through the full sequence of lubrication regimes. Figure Three shows the entrainment velocity on a typical cam and follower arrangement. For most of the engine cycle, the cam, lubricated by splash will be in a fully hydrodynamic regime against the follower. However the figure shows that at certain points around the cycle the entrainment velocity actually drops to zero and reverses.

While the reverse entrainment direction is not a lubrication issue, the reversion from full hydrodynamic to the boundary regime will increase both friction and wear at these positions. Examination of the lobes on camshafts can often reveal polished areas either side of the 'nose' where this effect is in operation and not on the nose of the cam, where one might expect.

Figure.3



The bearings, particularly the big-end bearings are often the area most sensitive to oil viscosity since they operate almost exclusively in the full hydrodynamic regime.

Ideally, in order to minimise friction, we would wish to operate an engine on the least viscous lubricant available. However, in our wish to make engines ever more compact (particularly in the case of 'V' designs) bearing sizes in terms of width as well as diameter may be restricted. The difficulties of minimising the pressure losses in the oil system to the bearings and overcoming the centrifugal action of the crankpin may also have to be addressed. Thinner oils therefore need tighter clearances between bearing and journal or flow rates may have to be increased which means a bigger pump.

After all this you have to be aware that lubricants also exhibit the phenomenon of temporary viscosity loss, which increases as the shear rate increases. Since the maximum shear rate in most normal engines is around 1,000,000 and the typical maximum bearing oil design temperature is likely to be in the order of 150 deg C, this reduced actual viscosity will need to be included in any consideration to do with bearing design.

The Society of Automotive Engineers have developed the concept of High Temperature/ High Shear to further classify lubricants and have included it in the recent updates of J300 (see Table Two). Therefore despite our wish to run on the lowest viscosity oil possible (to minimise oil system friction losses) the HT/TS needs to be considered.

Although many racing engines run on 30 and 40 grade oils occasionally some have to run on 50 grades. Anything greater than a 50 grade for a modern engine suggests, in my opinion, that the power unit may not have been designed to make the optimum use of the lubricant.

The design of the lubrication system at this point is therefore not quite as simple as it may seem but once again the lubricant manufacturers are controlling the critical parameters to ensure robust designs.

As I said in my opening statement, the engine lubricating oil is probably the most complex component in a race engine and limited space has allowed me to cover only a limited selection of topics in the briefest of detail. Readers who may wish to know more may like to know that the author from time to time runs engine lubricant awareness courses around the UK. Anyone interested in these may contact me via the editorial offices of this magazine or e-mail me directly on IPPLtd@tesco.net

