

LIMITS - THE ROBOTS OF OIL ANALYSIS

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Introduction

Questions on limits on oil analysis parameters, such as wear levels, additive levels and viscosity are high on the list of those that the WearCheck diagnosticians field most often. "When is the iron too high?", "how much viscosity increase is acceptable?" and so on and so forth. Unfortunately, there are not always hard and fast answers to these questions; in fact there are seldom such answers.

Limits are the oil analysis equivalent of robots. (For our international readers, a "robot" is the South African word for a traffic light). Robots cannot force your behaviour at an intersection, they merely indicate that a decision is required on your part and give a suggestion on how to proceed. There may be a good reason why it is not safe to proceed on a green, and

(occasionally) there may be a similarly good reason to ignore a red.

Limits are devices used in oil analysis, as in many other technologies, to alert the user to abnormal, or potentially abnormal, situations. Limits are relatively easy to set, and this article will examine some of those methods. It is the interpretation of the difference between "abnormal" and "potentially abnormal" that makes the subject of limits an art more than a science.

The process of diagnosis of used lubricant samples can be defined as "the determination of the acceptability, or unacceptability, of a particular laboratory result by the application of limits interpreted in the context of other laboratory readings and the operational environment in which the component operates". That sounds like it was written by a lawyer, and that's also about as vague as a definition can get, but it's true. A more relaxed, but equally as vague, definition might read "diagnosis of used lubricant samples is the black magic of balancing science, art, gut feel and experience by applying limits determined by past history and the operating environment of the component".

As an example, a copper concentration of 200 parts per million (ppm) might be acceptable in one situation, and yet, in another identical engine, a copper concentration of 20 ppm might be cause for alarm. The condition of the oil, for example heavy sludge contamination or water contamination, might require that some results be treated differently or even ignored. That is why WearCheck employs diagnosticians; they are trained to recognise these anomalies and comment accordingly. And, let's be honest, there is as much of an element of art as there is science in the interpretation of oil analysis laboratory results. There's a good reason why there is a sign on the door of the room where we do our most advanced testing which reads "The Crystal Ball Room".

Limits are contextual decision points, not decisions

Let's call a spade a spade: if the art of setting and using limits could be converted into a science, then oil analysis diagnostics would be computer algorithms, not humans. Training a diagnostician takes four to six months, and about 30 000 samples which need to be vetted by a qualified diagnostician before they are released, so it's really not something that can be condensed into six or eight pages. If you plan to take away from this bulletin a list of cut-off numbers applicable in any situation, then save yourself some time and stop right here. But if you wish to learn more of the process of setting and interpreting limits, then read on.

Trending tool

The most important thing to know about oil analysis, again the same in many other condition monitoring technologies, is that the technique is a trending tool. In many cases, perhaps most cases, the absolute values returned by the laboratory instruments themselves are meaningless. What is meaningful is how the numbers have changed since the last sample. When limits are used in this context, they become very powerful tools. In order to ensure that limits are effective, an effective oil sampling programme must be in place.

The three aspects of oil analysis

Oil analysis may be broken down into three different categories, as you see them laid out on your report. They are:

- Additive and lubricant condition
- Fluid contamination
- Machine wear

One cannot apply the same limits to each category, as will be seen later.

Severity of limits

Typically there are two levels of severity: caution and critical. When a caution limit has been exceeded it means the parameter must be monitored closely. When a critical limit is exceeded it means immediate action must be taken. Three consecutive instances of a parameter exceeding a cautionary limit should be treated as if the critical limit had been exceeded.

Limits can be set on the high side, the low side or, in some cases, both. These are illustrated in Figure 1, Figure 2 and Figure 3 respectively.

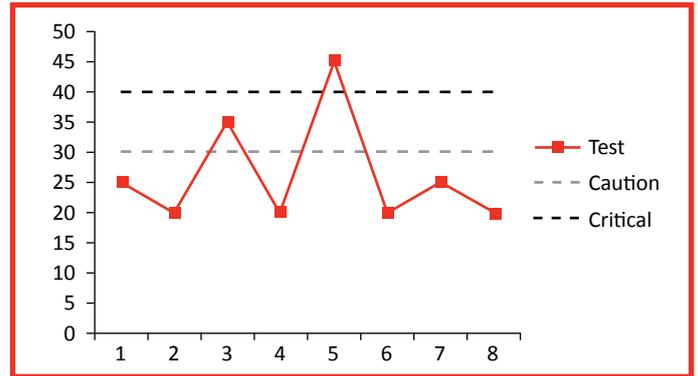


Figure 1: High-end limits

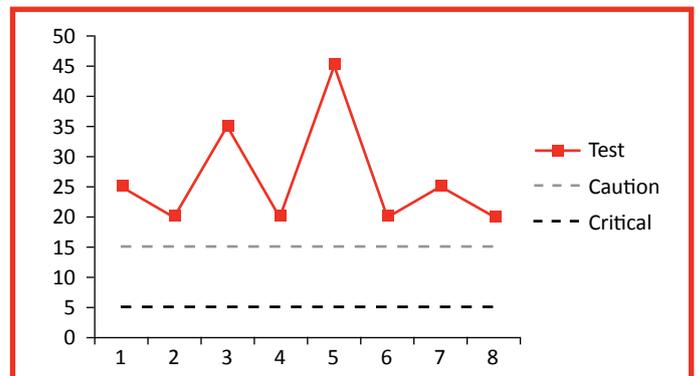


Figure 2: Low-end limits

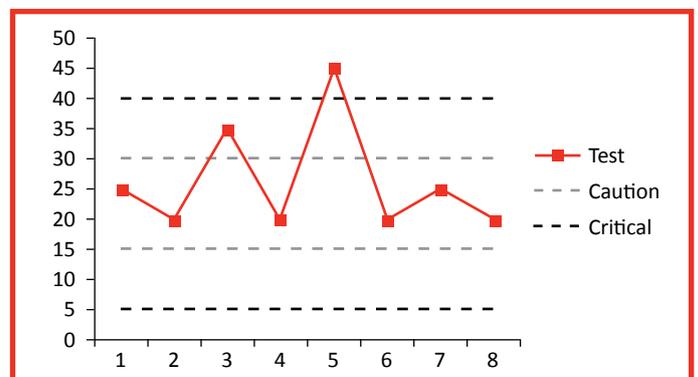


Figure 3: Both high-end and low-end limits

High-end limits would be applied to tests like wear metals and contaminant readings, low-end limits to tests like the total base number (TBN) or additive levels, and both to tests like viscosity which can go either way.

The effects of the time machine

Some parameters of lubricant condition, contamination and machine wear depend on how long the oil has been in use for, others do not. Thus limits can be broken down into two broad categories: those that are time-independent with respect to the period oil in use (POIU), also called absolute limits, and those that are time-dependent (relative limits).

Time-independent (absolute) limits

Time-independent or absolute limits are those that do not take into account the period the oil has been in use. These limits are primarily related to the first two categories of oil analysis, namely fluid condition and fluid contamination. Basically the way they work is this: if a parameter exceeds a pre-determined limit, then action must be taken. The POIU is irrelevant.

Absolute limits can be divided into subcategories:

- Targets
- Ageing limits

Target limits are designed to control the health of the machine. Targets are applied to those parameters that can effectively be controlled and reversed by maintenance interventions. Good examples are moisture content and particle count (solid particulate contamination). If either of these limits is exceeded, then corrective action like filtration or dehydration can be successfully applied.

On the other hand, changes to the oil itself like oxidation and (usually) viscosity cannot be reversed, so to these parameters we would apply ageing limits.

It doesn't matter whether the limit is a target or an ageing limit, the point is when the limit is exceeded we need to do something. The POIU is irrelevant.

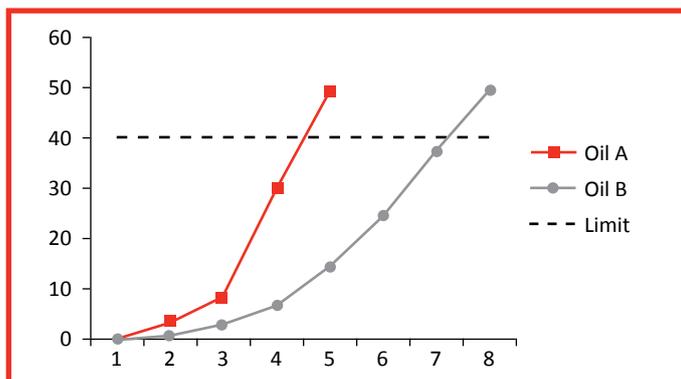


Figure 4: Absolute limits in action

Figure 4 demonstrates absolute limits in action. Oil A has degraded or become contaminated faster than Oil B. The time it has taken to happen doesn't matter in the slightest, the fact is that the limit has been exceeded and action must be taken.

Setting the limits

There are general guidelines available for setting absolute limits but, to be quite honest, they don't fit every situation. The best way to set these limits is by statistical analysis of past samples.

It is realised that one doesn't want to push the dirt level in the transmission of a 150 ton dump truck as an experiment to see how much punishment it can take. If you have any questions on what to use as a start, pick up the telephone and call the duty diagnostician or technical consultants at WearCheck. Remember, there is a combined diagnostic experience of 100 plus years there and at least you'll get a good starting point for your operation. Also remember that limits should be re-evaluated on a frequent basis, as operating conditions change continuously.

In summary, set your limits on fluid degradation and fluid contamination based upon past analysis of machine wear as a function of the contamination or degradation. Especially as far as contamination goes, different contaminants are going to affect wear differently; diamond ore is far more abrasive than dust found in a flour mill environment. The relationship between wear and contamination is exponential, and only experience can determine the levels of contamination that start to generate unacceptable wear.

Elemental analysis of additives

Elemental analysis of additives can cause some confusion. Take, for example, an engine oil that happens to contain 3 000ppm calcium (Ca) present as the detergent additive in the new oil sample. One would think that putting this oil into an engine and running it for a period of time would result in a decrease in the calcium level as the additive gets used up. In fact, theoretically, this will not happen. Calcium is calcium, and nothing short of a nuclear reaction can change that fact. Calcium, nuclear reactions aside, cannot morph into mercury or gold, so one should expect to see exactly the same levels of calcium in the used oil as the new. In practice, the calcium level could go up or down. It might go down as the calcium-sulphonate detergent breaks down into calcium oxides, which get trapped in the filter. It might just as well go up as volatile components in the oil evaporate, concentrating the additive in the oil.

Determining limits for additive concentrations using elemental analysis should be approached with care. Perhaps the only instance of reliable elemental analysis of additives is the case of borate-fortified extreme pressure lubricants contaminated with water - the boron level will plummet as the water washes the additive out of the base oil.

Time-dependent (relative) limits

Time-dependent, or relative, limits are usually used primarily for the third category of oil analysis, namely machine wear.

Before we get into the concept of time-dependent limits, we need to consider the concept of normalisation.

Normalisation

Normalisation is a process used to take into account:

- The period the oil has been in use
- Oil consumption (in certain circumstances)

As long as oil consumption remains fairly constant, normalisation for oil consumption is not necessary, but normalisation for time is always necessary. Normalisation for oil usage is beyond the scope of this bulletin and will not be considered further.

To normalise a laboratory reading for time, use the following formula:

$$R_N = \frac{R}{t} \times T$$

Equation 1: Normalisation for time

where R_N is the normalised value of a reading,
 R is the original laboratory reading,
 t is the period the oil has been in use (kilometres, hours or months in the case of industrial equipment), and
 T is the parameter being used to normalise R , often 15 000 kilometres, 250 or 500 hours or months (the same units as t).

The normal drain interval is a good value to use for automotive equipment and, for components that have many samples between drains (typically industrial machines or large hydraulic systems on mobile equipment), use the typical sample interval.

To illustrate the importance of normalisation for time, consider the wear profile for a machine using iron as a representative element for wear. Wear is a function of time; when the machine is drained and refilled with oil, the oil will, for all intents and purposes, have no iron in it. As the machine is used it will wear, and the iron readings will increase. When the oil is changed again, the iron reading will start off at nearly 0 again. This is illustrated in Figure 5 below.

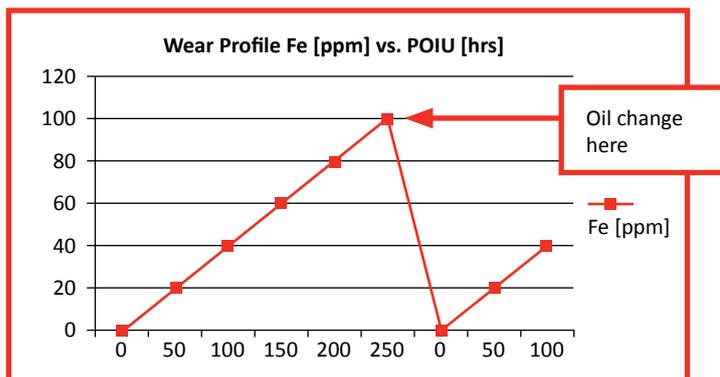


Figure 5: Normal wear profile

Consider an engine, which typically has a sample taken only every time it is drained, rather than multiple samples on the same oil fill. Table 1 below represents typical wear readings for each of seven samples.

Sample	Fe [ppm]
1	100
2	110
3	85
4	88
5	110
6	90
7	100

Table 1: Iron (Fe) results for 7 samples

Graphically, they may be represented as follows:

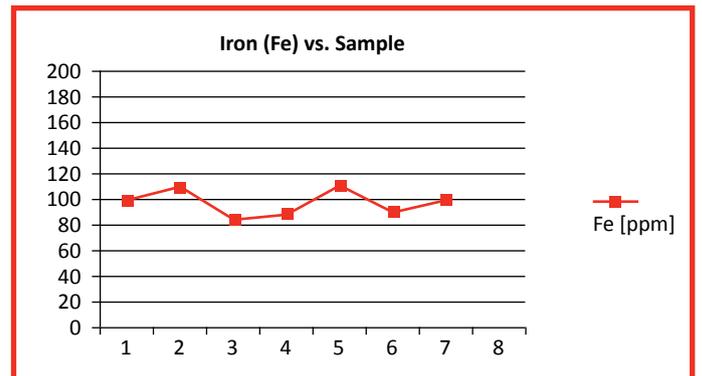


Figure 6: Iron readings versus sample number

So it would appear that the most wear is happening at samples 2 and 5. But, if we take into account the relationship between wear readings and time, as presented in Figure 5, and the period oil in use, as presented in Table 2, we see a different picture entirely.

Sample	Fe [ppm]	POIU[hrs]	Normalised Iron [ppm/250hrs]
1	100	250	100
2	110	270	102
3	85	150	142
4	88	180	122
5	110	275	100
6	90	230	98
7	100	250	100

Table 2: Iron readings have been normalised for time

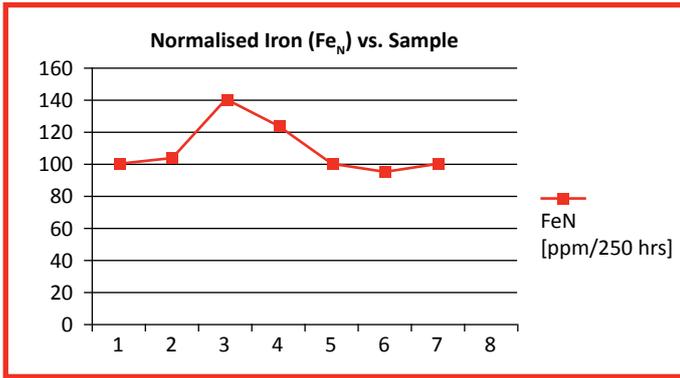


Figure 7: Normalised wear readings versus sample

Now, where previously samples 2 and 5 had appeared to be the problem children, this is no longer the case. In fact, where the wear in sample 3 in Figure 6 had actually appeared to be the lowest, the normalised values show the wear rate here was the highest.

It doesn't matter what divisor you choose to use for the rate calculation. Choose divisors that don't make the quotient look like either a telephone number or the diameter of an electron reported in metres; a good divisor would be the recommended oil drain interval for automotive components, be that 15 000 km / 250 hours or 1 month in the case of industrial equipment. Some people even use litres of fuel consumed to determine the rate of generation. Obviously, use the same divisor each time.

The example above considered an engine where, like most other automotive applications, there is only one sample taken during the oil's life, usually right when the oil is being drained. Normalisation can and must be applied to those other components that are sampled more than once during the oil's service life. Such components are more commonly found in industrial applications, where something like a conveyor gearbox or a hydraulic power pack might only be drained once a year, yet gets sampled once a month. In these cases, the wear versus sample number graph is like that represented in Figure 8 below.

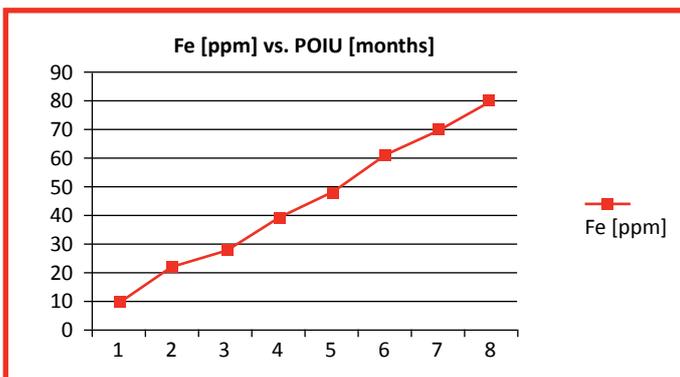


Figure 8: Normal wear profile for components with many samples between drains

Say for instance there was increased wear at sample 4. The wear versus POIU plot would appear as in Figure 9. One can see that sample 4 was an abnormality, but it is difficult to appreciate how bad it is.

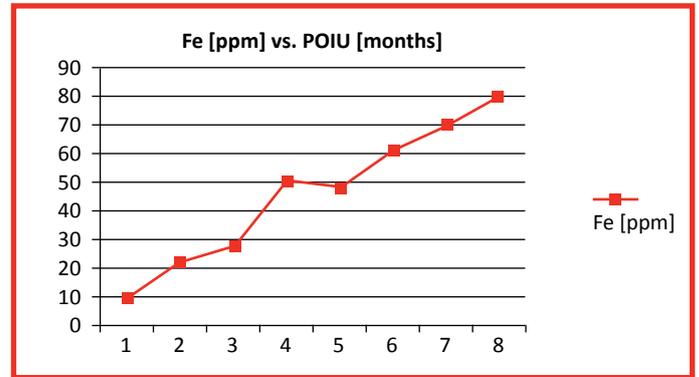


Figure 9: Increased wear at sample 4

By normalising the wear data, i.e. plotting rate of change rather than point-in-time values, the appearance of abnormalities is much more obvious. It is also a lot easier to apply graphical limit data to the plot, as shown in Figure 10 below. The data was normalised to iron generation per month. The data used to generate Figure 9 and Figure 10 is exactly the same. It is presented in Table 3 below.

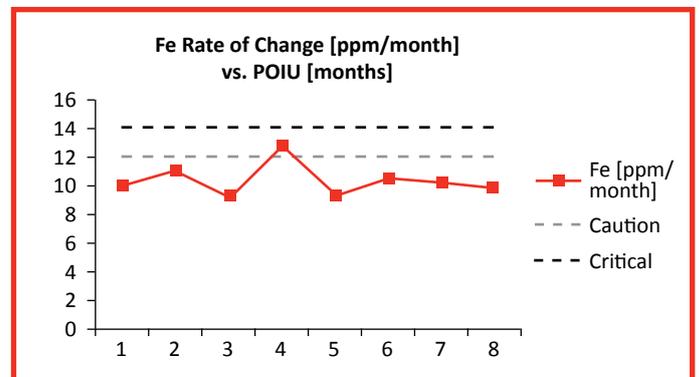


Figure 10: Normalised wear with limits superimposed

POIU [months]	Fe [ppm]	Fe [ppm/month]	Caution	Critical
1	10	10	12	14
2	22	11	12	14
3	29	10	12	14
4	50	13	12	14
5	48	10	12	14
6	61	10	12	14
7	70	10	12	14
8	79	10	12	14

Table 3: Wear data for component with many samples between drains

To recap, as far as normalisation goes, these are the key points to remember:

- Wear readings (time-dependent parameters) should always be normalised for time before applying limits
- Additive and contaminant readings (time-independent parameters) should never be normalised for time before applying limits

Setting the limits

Determining the numbers for relative limits is best approached statistically. The process would typically be as follows:

1. Gather the data for the previous 10 or 20 samples
2. Normalise for time
3. Calculate the mean
4. Calculate the standard deviation
5. Calculate the limits

The cautionary limit would be defined as:

$$L_a = \bar{x} + \sigma$$

Equation 2: Calculation of the cautionary limit

where L_a is the alarm (caution) limit,
 \bar{x} is the mean, and
 σ is the standard deviation.

The critical limit would be defined as:

$$L_c = \bar{x} + 2\sigma$$

Equation 3: Calculation of the critical limit

where L_c is the critical limit.

Sometimes

$$L_c = \bar{x} + 3\sigma$$

Equation 4: Alternative calculation of the critical limit

is used instead.

As an example, ten wear readings are presented in Table 4.

Sample	Fe [ppm]	POIU[hrs]	Fe [Norm]
1	35	250	35
2	40	265	38
3	55	180	76
4	30	240	31
5	35	248	35
6	28	210	33
7	60	270	56
8	30	250	30
9	35	260	34
10	30	250	30
		Mean	40
		Std Dev	15

Table 4: Wear readings

The readings are normalised, and the mean and standard deviation are calculated.

Figure 11 represents this data graphically.

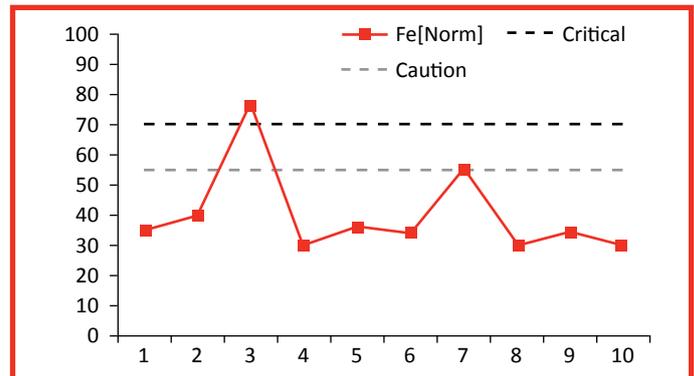


Figure 11: Normalised wear readings with calculated statistical limits superimposed

There are other factors which come into consideration when using statistical limits. These include:

- The age of the machine
- The type of operation
- The environmental conditions

These should be taken into account. As machines age, their wear pattern changes.

The type of operation will also influence the wear patterns; for instance, if a dump truck is being used to move quarry sand for a few months, then gets used to haul rocks in an ore mine, the wear readings are likely to pick up in the latter operation.

And, if the dump truck is being operated in tropical climates where for six months of the year the haul road is baked as hard as rock, and for the other six the truck is fighting mud up to its axles, the wear readings just have to be higher in the rainy season. For this reason it is probably best to use the last ten readings or readings from the last six months or so to generate the limits, rather than use all the readings over the life history of the machine.

Contradictions

So far we've approached limits from a fairly theoretical viewpoint. But this is the real world, and in the real world there are always contradictions. There are always those other motorists out there that either fall asleep at green robots, take an orange light as a signal to accelerate hard, or see a red light as a personal challenge to accelerate even harder. Adhering to the colour of the lights will never guarantee safe passage through the robot. This is why the human factor of interpreting limits will never be replaced by a computer. Let's look at a couple of examples of contradictions.

In a corrosion situation the type of wear particles that are produced are very small, mostly submicron in size. On your oil analysis report this translates into high elemental iron (Fe in ppm) readings, and low ferrous density (PQ) readings. Whilst not desirable, this is unlikely to indicate that the end of the machine's life is just around the corner. Delaying action here is probably not a problem, as long as it's not delayed too long. This is an example of jumping the red robot fairly safely.

At the other end of the scale, one can get low Fe readings and critically high PQ readings. This is typical of a fatigue or adhesion wear situation, and catastrophic failure is imminent. Jumping this red robot could get you into a lot of trouble.

Let's take a look at another example. The fuel dilution readings are slightly higher than normal, the soot readings are higher than normal and the viscosity has not changed. Reduced viscosity from the fuel dilution has combined with increased viscosity from the soot contamination to have a near zero net effect. If you were concentrating on viscosity to determine a fuel dilution problem then you would jump this red robot with expensive consequences.

And on top of that there is still always the possibility that the sample was taken incorrectly. Only human analysis of the limits, in the context of the sample's situation, can determine the correct, or probably correct, steps to resolution of the problem.

Kick-off point

The table below gives a kick-off point for setting limits. These are not limits that are necessarily used by WearCheck given the wide variety of operations, equipment and duty cycles that we experience but, for someone setting up a limit programme, they are a starting point that can later be refined to fit one's particular requirements.

Test	Application	Base Point	Critical Low	Caution Low	Caution High	Critical High
Viscosity	Engine	New oil sample	-10%	-5%	+10%	+20%
	Non-engine	New oil sample	-10%	-5%	+5%	+10%
Moisture	Engine	-	-	-	0.1%	0.2%
	Drivetrain	-	-	-	0.4%	0.8%
TBN	Engine	New oil sample	2	50% of new oil	-	-
TAN	API Groups I – IV	New oil sample	-	-	New oil + 0.2	New oil + 1.0
	API Group V ¹	New oil sample	-	-	?	?
Additives ²	All	New oil sample	-25%	-10%	-	-
Silicon ³	Engines	-	-	-	25 ppm	100 ppm
	Automotive gear	-	-	-	100 ppm	300 ppm
	Industrial gear	-	-	-	25 ppm	50 ppm
Soot	Engine	-	-	-	150-250 ⁴	250
Oxidation ⁵	Engine	-	-	-	21	23
Sulphation ⁵	Engine	-	-	-	35	40

¹ Check with component and lubricant OEMs

² Use these limits with caution

³ Refers to silicon contribution from dirt only

⁴ Varies depending on oil type, viscosity and engine design

⁵ Can be affected by soot readings

Table 5: Some kick-off point limits

The application of limits

This should go without saying, but it is being said anyway: the strength of the lubricant analysis programme and the setting of meaningful limits relies totally on the strength of the lubricant sampling programme; erratic sampling leads to unreliable trends and unreliable statistical data.

Unreliably taken samples can result in one of two scenarios:

- The sample which is contaminated with other substances introduced during the sampling procedure can result in a lot of wasted time and effort looking for a problem which does not exist.
- The other scenario, the potentially more serious one, is that the sample is extracted from a point which is not representative of the lubrication system as a whole. A good example is taking a sample after a filter, and another is taking a sample from a reservoir where dilution of wear metals and contaminants can result in a serious situation being missed.

Following that, for the successful application of limits, consider:

- Having a few samples each from a few similar components in similar operation for comparison purposes.
- Using the limits suggested in Table 5 above as a starting point.
- Examining your limits regularly. If none of the data ever even closely approaches the suggested limits, then tighten the limits up. If your data regularly exceeds the suggested limits, then it's time to ascertain whether there is genuinely a problem or whether

the limit exceptions are a peculiarity of your operation; that's a decision that can only be made by a human with other data and knowledge to back it up, and not with any computer algorithm in existence today.

- Re-evaluating your limits on a six-monthly or annual basis. Changes in duty, lubricant technology, maintenance procedures, operating conditions and many other factors can require a tweaking of limits.

In summary:

- Limits are a tool to alert users to abnormal or potentially abnormal behaviour. They are tools designed to focus attention and possibly raise some questions but they are not a substitute for human judgement.
- Meaningful limits assume a sound oil sampling programme, with good samples being taken regularly.
- Lubricant health and lubricant contamination parameters usually use time-independent or absolute limits.
- Machine wear limits usually employ time-dependent or relative limits.
- Machine wear test results should be normalised at least for time and, possibly, for oil consumption.
- Interpretation of the limit exceptions should take into account duty cycle, machine age, lubricant age and environmental conditions.

So, the next time you approach a robot, take a moment to look around, take into account information that the robot has not noticed, and only then make your decision on how to proceed safely.

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