LUBE-TECH

NO.25

OIL CLEANLINESS

The effectiveness of lubricants in preventing wear can be seriously compromised by the presence of contaminants such as particulates and water in the lubricant.

Where sliding surfaces are separated by an oil film (hydrodynamic lubrication), wear rates of the two surfaces arising from the presence of particulate contaminants increase rapidly when the sizes of the particles exceed the running clearances between sliding surfaces.

The quantity and size of particulates in the lubricant is therefore one of the most important factors affecting the service life of the lubricated components of all machinery. (For the purposes of this article, and in keeping with common industry practice, the terms "clean" and "cleanliness" refer to the amount and size of particulate contamination in a lubricating or hydraulic fluid). The effect of particulate contamination varies with the type of system and lubrication environment, in that some environments are more sensitive to particulate contamination than others. In hydraulic systems, for example, clean fluid is absolutely essential for successful long-term operation. Also, machines equipped with rolling element bearings are especially sensitive to particulate contamination, although machines using fluid-film bearings are not immune to such damage. Many sources cite dramatic improvements in expected machine life resulting from even modest improvements in lubricant cleanliness.

QUANTIFICATION OF PARTICULATE CONTAMINATION.

The question of quantification of oil cleanliness raises a number of issues such as

- How clean is "new" oil?
- How clean does the oil need to be?
- What improvements in machine life can you expect from cleaning up your oil?
- What about other types of contamination?
- What steps can you take to clean up your oil?

The standard test procedure for assessing the cleanliness of hydraulic fluids is ISO 4406, which establishes the relationship between particle counts and cleanliness. Although originally developed for application to hydraulic fluids, common practice has now extended the application of the standard to many other types of lubricants. This international standard uses a code system to quantify contaminant levels by particle size in micrometers (µm). Using ISO 4406, a machine owner/operator can set simple limits for excessive contamination levels, based on quantifiable cleanliness measurements.

ISO Code	Minimum	Maximum
10	5	10
11	10	20
12	20	40
13	40	80
14	80	160
15	160	320
16	320	640
17	640	1300
18	1300	2500
19	2500	5000
20	5000	10000
21	10000	20000
22	20000	40000
23	40000	80000

Table 1. ISO 4406 fluid cleanliness codes (particles per ml.).

Table 1 illustrates the ISO 4406 cleanliness codes. (The ISO standard calls the codes "scale numbers." They may also be referred to as "range numbers" and represented as R_5/R_{15} for 2-part codes and $R_2/R_5/R_{15}$ for 3-part codes.) This standard allows the quantification of current particulate cleanliness levels and also to set targets for required cleanliness levels. The current standard provides a 3-part code to represent the number of particles per millilitre (ml) of fluid greater than 2 µm, 5 µm, and 15 µm, respectively. The current standard is ISO 4406:1987(E). The ISO is now circulating a draft proposal, ISO/DFIS 4406:1999(E), for contamination levels measured with automatic particle counters calibrated in accordance with ISO 11171. In the proposed standard, the three parts signify the number of particles/ml greater than 4 µm, 6 µm, and 14 µm respectively (scale or range numbers $R_4/R_6/R_{14}$).) Many laboratories will report either a 2-part code, or a 3-part code, as specified by the user. The 2-part code refers to particle counts in the 5 µm and 15 µm size ranges. A 3-part code of 17/14/12, for example, would indicate 640 to 1,300 particles/ml greater than or equal to 2 µm, 80 to 160 particles/ml greater than or equal to 5 µm, and 20 to 40 particles/ml greater than or equal to 15 µm. Notice each step in the ISO code represents either double or half the particle count relative to an adjacent code. It is important to note the "/" character in the written form of the code is merely a separator, and does not signify a ratio of the scale numbers.

Studies of "new" turbine oils, crankcase oils, hydraulic fluids, and bearing oils delivered to customers indicate varying degrees of cleanliness, with ISO codes from a low of 14/11, to as high as 23/20. Drum-delivered products were generally found to be cleaner than bulk-delivered products. Referring to Table 1, one might think twice before putting "new" oil with an ISO 23/20 measurement in a machine. Improper storage procedures can contribute additional contamination to new oil. Poor handling practices are another source of new oil contamination. It is important to identify all vessels are used in the plant for transporting and adding makeup oil, and to ensure that they are in an adequate state of cleanliness. After implementing cleanup programs, many users find the dirtiest oil in their plant is incoming "new" oil. It is clear that proper filtering of new oil during or before filling is a prudent and highly desirable practice to extend machine life. Each machine class should be evaluated for cleanliness levels appropriate to the application. In general, machines with tight clearances and/or anti-friction (rolling element) bearings benefit greatly from very clean oil. Turbine electro-hydraulic control (EHC) systems and many aero-derivative gas turbines are examples of industrial machines that require extremely clean oil for proper performance and long life. Filter systems rated to remove particles as small as 3 µm to 7 µm are commonly used in such applications. Hydraulic systems' targets should also be adjusted to cleaner levels for higher system operating pressures.

Table 2 presents some typical base lubricating oil cleanliness targets for common machines and machine elements. Like most guidelines, these targets are suggested as starting points. It may be necessary to make adjustments to these levels once the response of machinery on a particular site has been evaluated.

Machine/element	ISO Target
Roller bearing	16/14/12
Journal bearing	17/15/12
Industrial gearbox	17/15/12
Mobile gearbox	17/16/13
Diesel engine	17/16/13
Steam turbine	18/15/12
Paper machine	19/16/13

Table 2. Typical base cleanliness targets.

Studies performed in many industries all show dramatic extensions in expected machinery life by improving lubricant cleanliness. In one example, a reduction of particles larger than 10 µm from 1000/ml to 100/ml resulted in a 5-fold increase

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in machine life, which must be an attractive return on cleanup investment. An additional benefit of cleaner oil is a lower noise floor for wear particle detection measurements. It is much easier to detect subtle changes in the amount of wear debris in a clean system than in a dirty one

The Society of Automotive Engineers (SAE) studies have shown engine wear reductions of 50% when filtering crankcase oil to 30 µm, and 70% when filtering to 15 µm, as compared with filtering to 40 µm. However, some investigators have reported that the presence of a certain concentration of fine sub-micron particles was beneficial as they aided polishing of bearing surfaces over an extended period thereby reducing friction.

Lubricant film thickness in fluid-film journal bearings is substantially larger than that found in rolling element bearings, and hydrodynamic pressures are typically lower. However, the Babbitt in these bearings, being composed primarily of lead and tin, is susceptible to oxidation damage from water and oxygen. Water can also reduce the load-carrying capacity of a fluid-film bearing lubricant sufficiently to cause journal-to-bearing contact (wiping). The reduction in film thickness also increases the in order to establish and maintain an oil clean-up programme it is necessary to: -

- Measure and evaluate current cleanliness levels to establish baselines for comparison.
- Examine and evaluate current storage and handling practices.
- Set cleanliness targets based on your goals for longer machine life and/or reduced maintenance and downtime costs.
- Evaluate, select, and implement the improvements in filtration, storage, and handling procedures required to achieve the goals.
- Measure and trend your progress.
- Document the impact of your investment on availability, maintenance expense, and machine life.

With these elements delineated, some of the practical aspects of improving filtration, storage, and handling procedures can be addressed.

Many improvements to your filtration, storage, and handling procedures can be made with minimal cost. A little time spent simply reviewing your current storage and handling procedures can be revealing. During the evaluation phase, it is important to identify contamination sources as well as the levels. Contamination sources may include:

- **Contaminated new oil.** As previously mentioned, new oil is often not as clean as you might think, usually becoming contaminated during transportation, storage, and handling.
- **Built-in contamination.** Machine components can become contaminated from handling practices encountered during overhauls or rebuilding processes. It is important to review shop procedures relating to cleanliness of internal wetted parts, hoses, and lubricant piping.
- **Ingested contamination.** Unfiltered sump vents and faulty seals are common problems, which can result in contaminants (including water as well as particulates) entering the lube system from the outside environment. Minor modifications to vent systems can reap rewards in this area.
- **Internally-generated contamination.** Recirculating wear particles through machine components can create a self-fulfilling prophecy of machine destruction. Normal full-flow filtering removes some, but not all, wear particles. In fact, many full-flow filtration systems are only effective in removing particles larger than 40 µm. Concentrating on the hardest and most abrasive particles is an effective strategy for this category of contaminants.

Once the contamination sources are identified, you can concentrate on the areas most likely to generate your target cleanliness levels.

Consider the case of a typical practical application, i.e. a diesel crankcase lubricant filtration system.

A full-flow **Barrier** filter will normally have a pore size ranging from 15 – 50 µm, although differences often arise in the figures quoted due to confusion over the use of absolute vs. nominal filter ratings. Such barrier media filters are therefore normally only capable of removing the largest contaminant particles, and will not cope with accumulation of soot, the pore sizes being at least an order of magnitude larger in pore size than the majority of particles circulating in the lubricant. To provide a full-flow filter which would remove particulate debris of less than 1µm, the filter would need to be unacceptably large in order to obtain acceptable flow rates and pressure drops. However, if a small proportion, normally some 10%, of the lubricant is diverted through some form of by-pass filter which is effective in retaining these very small particles, the lubricant will eventually achieve a high level of cleanliness, if the filtration removal rate exceeds the generation rate of the small particulates, which is the case in practice. A variety of by-pass filter types have been evaluated, all of which are generally effective in purifying the lubricant to a greater extent than is possible with the normal full-flow filter, but there are differences in qualitative and quantitative performance levels according to the filter type. A number of papers have been published on the subject of the use of by-pass filtration systems

Barrier filtration of particulate material to the sub-micron level is possible, but the system suffers from a number of drawbacks. As the filter becomes progressively loaded with contaminant, the flow rate through the filter drops, falling to zero when the filter becomes completely blocked. However, before this stage is reached, the filter membrane may well rupture or channel at high inlet pressures, allowing unfiltered oil to pass through. Filtration Ratings of barrier media filters is expressed as either the Filtration Ratio β, or the Filtering Efficiency η.

$$\beta = C_{Up} / C_{Down}$$

Where C_{Up} = Concentration of particle entering the filter
C_{Down} = Concentration of particles leaving the filter

The particle count size is normally expressed as a subscript, e.g. a filter with a rating of "$\beta_2 = 100$" would allow one particle through for every 100 particles of size 2 µm entering the filter. The Filtering Efficiency η is defined as the Upstream – Downstream Particle Count of a given size (x) divided by the Upstream Particle Count, i.e.

$$\eta_x = (1-1/\beta_x) \times 100$$

There are a number of standard test procedures to evaluate filter efficiencies over a period of time as the filter blocks. Since filter blocking results in an increase in the differential pressure drop across the filter, test procedures also measure this pressure drop. In Test Procedure J1858, the times taken for the pressure drop to increase by 80% and 100% respectively are recorded, and upstream and downstream particle counts are evaluated simultaneously every 10 minutes. This test procedure stipulates the use of test oil conforming to SAE J1260, and a contaminant conforming to SAE 5 – 80 µm.

Test Procedure ISO 4572 records the time taken for the initial pressure drop to increase by 5%, 10%, 20%, 40%, 80% and 100% respectively. The oil type is specified within the standard and the contaminant is specified as Air Cleaner Fine Dust or any other ISO-approved equivalent. Methods for evaluating filtration efficiencies are fully described in a number of standard procedures, including:

SAE Standard No. J1858, 1988, "Full Flow Lubricating Oil Filters – Multi-Pass Method for Evaluating Filtration Performance".

SAE Standard No. HS-806, 1994 "Oil Filter Test Procedure".

SAE Standard No. J1985, 1993 "Fuel Filters – Initial Single-Pass Efficiency Test method".

ISO Standard No. 4572, 1981 "Hydraulic Fluid Power – Filters – Multi-Pass Method for Evaluating Filtration Performance".

One such type of by-pass barrier filter, developed and proven in the US using technology based on human blood dialysis, diverts a small continuous stream of engine oil (5%-7%) through a specially designed filter element that uses a machine wound string of cotton/cellulose fibre. As it cleans the oil, the filter traps particulates down to 3 microns and removes water. This system claims to overcome channelling by using computer controlled winding machines that control both weave and tension of the wind to produce woven filter elements. These are wound on a stainless steel core resulting in a varying density filter progressing from a 40 micron weave at the outer diameter to a 1 micron capability at the core. The weave is designed so that there is an equal resistance to flow throughout the filter. With no shortcuts available, the oil must pass completely through the filter element.

This system is also claimed to remove water as a result of an 80% cotton content in the makeup of the filter element which retains moisture in suspension within the individual fibres until it reaches saturation. This compares with paper/wood cellulose, glass or synthetic fibres used in conventional full flow filters which are virtually ineffective in absorbing water.

This system has been extensively trialled in the US, where the tripling or even quadrupling of oil life has been claimed.

A further development of the barrier filter incorporates a heating chamber, or **'refiner'** the purpose of which is to remove water, unburnt fuel, acids, antifreeze and other low-boiling contaminants from the lubricant on a continuous basis.

As destructive as particulate contamination can be, these other contaminants also contribute to oil degradation and premature machine wear. Water alone is a significant factor in lubricant degradation. When combined with iron or copper particles, water becomes even more aggressive in attacking lubricant base-stocks and additives. The adverse effects of water in oil include:

- Lubricant breakdown, through oxidation and additive precipitation.
- Changes in viscosity, affecting the ability of a lubricant to maintain the film thickness necessary to protect the lubricated surfaces.
- Corrosion.
- Accelerated fatigue of lubricated surfaces.

Even very small amounts of water can be harmful in machines equipped with rolling element bearings.

These refiners have also undergone extensive trials, and lubricant lifetimes in excess of 800,000 miles have been claimed in commercial diesel engines. In practice, the lubricant first passes through a fine barrier-type filter, of a type similar to that described above, after which it passes into the heated evaporation chamber in the form of a thin film, where, after heating to temperatures ranging from 100 to 150°C, the subsequent pressure drop to atmospheric assists the rapid removal of the lower-boiling contaminants described above. The vented contaminants are directed back into the induction system and subsequently consumed during the combustion process. In practice, it has been found that an operating period of some 10,000 miles was necessary for the refiner to clear the lubricant of contaminants, regardless of whether the engine was new or old, and, once cleared, the lubricant remained virtually free of harmful solids and liquids. For reasons which have not satisfactorily been explained, it appears that the lubricant which has been subjected to the cleaning up treatment by such a refiner is claimed to have an improved film strength compared with the original, which, as would be expected, results in decreased wear of engine components.

Again, for reasons which are difficult to comprehend, tests have shown that the emission levels of NOx, carbon monoxide, particulates and smoke are reduced when such a refiner is incorporated into the lubrication system, after an initial acclimatisation period. These systems would be most beneficial when used in vehicles subjected to intermittent use with frequent need for cold starts, e.g. school buses. It is this pattern of use which is most likely to result in the problem of fuel dilution of the lubricant. If the lubricant becomes excessively thinned by fuel dilution, the hydrodynamic barrier which separates the moving parts within a bearing becomes thinner and less durable, with the consequence that the smaller particles within the oil become effectively more abrasive. This problem would be most readily overcome by using a refiner to evaporate off the lower-boiling fuel. Such refiners are also effective in eliminating 'acid-pitting', which is caused by an accumulation of acidic by-products in the lubricant.

A further option is the use of a **Centrifugal** filter.

By-pass Centrifugal oil cleaners may be externally powered or self-powered. The latter type are generally much smaller, and can be used in a variety of fixed (e.g. cleaning of quench oils and hydraulic oils) and mobile (e.g. commercial vehicles) applications. In a typical example, the centrifuge cleaner will consist of a body with outer casing and a central spindle around which a rotor revolves at high speed. The oil, which is under pressure, enters the centrifuge body and continues to the cleaning chamber of the rotor via the centre spindle. Having passed through the cleaning chamber, the oil exits at the base of the rotor via tangentially opposing nozzles. The oil exiting from the rotor causes the rotor to revolve at high speed, i.e. up to 10,000 r.p.m. Thus creates a centrifugal force within the rotor which can exceed 3000g, which causes separation of contaminants which differ in density from that of the oil. They migrate outwards, forming a dense 'cake' on the inside surface of the rotor wall. The rotor may then be either cleaned out or replaced with a new unit at the appropriate time. For optimum performance, it is essential that the oil entering the centrifugal filter is as hot as possible, so that the density and viscosity are at their lowest which will facilitate the migration of contaminants. Also, the oil should be delivered at high pressure, so that high centrifuge speeds are obtained, generating high centrifugal forces. The ideal positioning for the centrifuge cleaner is therefore immediately downstream of the oil pump. It is also necessary to ensure that oil drainage route from the cleaner, normally directly back into the sump, is free of any obstruction so that no flooding of the rotor can occur which would reduce its speed.

The basic principles involved are fairly basic and simply explained. Consider the case of a spherical contaminant particle of diameter d_p

and density ρ_p suspended at a radius r in a fluid with density ρ_0 and dynamic viscosity μ_0. If we then asume that the fluid and the contaminant particle are both rotating about a vertical axis at the same angular velocity ϖ, then the centrifugal force acting on a particle would be:

$$f_c = m_p r \varpi^2$$

where:

f_c is the centrifugal force acting on the particle

m_p is the mass of the particle

r is the radius

ϖ is the angular velocity.

Opposing this force is the effect of the viscous drag upon the particle (f_d) which is a function of the Reynolds number and the particle drag coefficient. If we assume that Stoke's law will apply to the migrating rate of the particle, then the time taken τ for the particle to travel a distance r to the rotor wall is

$$\tau = \frac{18\mu_o \ln((r + \Delta r)/r)}{d^2_p \Delta\rho\varpi^2}$$

where $\Delta\rho$ is the difference in density between the contaminant particles and the oil (ρ_p - ρ_o.)

From this last equation, it follows that separation of the particles is more rapid the lower the viscosity of the oil, as would be expected. Also, the shorter the distance that the particle has to travel under a given set of throughput conditions, then the smaller is the size of particle which can be removed.

The superiority of the performance of centrifugal cleaners of this type compared with conventional barrier filters has been thoroughly investigated under laboratory conditions and in practical trials.

This type of cleaner will not separate out unburnt fuel, but does have other advantages compared with barrier type filters in that the cleaning efficiency remains constant throughout, also particles smaller than those which may pass through many barrier filters may be separated out. In practice, primary soot particles below 1µm, which are responsible for oil thickening, may be separated out using centrifugal systems. The benefits of the centrifugal by-pass filtration system in reducing wear values can be quantified by measurement of the increase in iron levels in the lubricant. It has been shown that the rate of increase in iron levels in an engine equipped with a centrifugal filter is only half that compared with an engine operating without the benefit of a centrifugal filter.

General water contamination

Since the sources for water contamination are so numerous and ubiquitous, eliminating all sources of moisture can be very difficult. Removing water from oil can also be a challenging task, but there are several methods available for use in general, non-automotive situations. Each method has advantages and disadvantages, so each must be carefully evaluated for the particular application. Some of the common methods for removing water from oil, along with their tradeoffs, include:

Settling/Evaporation

Natural - gravity acts on the water to separate it from the oil, and water escapes from the fluid via natural evaporation.

Inexpensive.

Least effective of known methods.

Properly-designed reservoir is required.

Only free water is removed.

Centrifuging (Centrifugal Separation)

Only the free water form of water is removed to about 20 ppm by weight, above the saturation point.

Entrained gases aren't removed.

Emulsified water content tends to increase.

Dirt and other solids are removed.

Additives can be removed by this method.

Coalescing Filters/Screens

Only free water is removed.

A coalescing cartridge filter is used to separate the water from the oil.

Additives can be removed by this method.

Only effective for narrow ranges of viscosity and specific gravity.

Some manufacturers claim "No removal of additives."

Filter/Dryers

Cartridge-type filters that use super-absorbent materials to soak up water.

Dissolved water isn't removed.

Vacuum Treating (Vacuum Dehydrating)

The wet lubricant is heated in a vacuum to separate the water.

Additives usually aren't removed from the lubricant, since it is a chemical separation.

Dissolved, emulsified, and free water can be removed.

When combined with effective filtration media, capable of being a highly-effective lubricant purification system.

Gas Sparging/Air Stripping

The chemical separation principle of air stripping is used.

Dissolved, emulsified, and free water are removed.

Additives are not removed.

Nitrogen or air can be used.

Finally, an additional cleanup step, which is often overlooked, is to specify the cleanliness levels of the lubricants you purchase. You may pay a little more up front, but the savings in machine availability, filtration costs, and machine life extension often more than offset the additional cost. If you choose this route, be sure to test the incoming oil to verify you get what you paid for.

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