

# Lubricant Cleanliness Application Note

## Introduction

After selection of the **correct** lubricant, the next most critical factors to long machine and lubricant life are keeping the lubricant **clean** and **dry**. Details such as machine criticality, operating environment, and component clearances as well as lubricant type, viscosity, flow rate, and economic issues must be carefully considered for optimum lubricant contamination control. This Application Note provides information that should be considered when designing a contamination control system to provide the best value. The specifics of each application are different and must be evaluated individually.

## Importance of Lubricant Cleanliness

### Machine Condition

In any machine application, the most important aspect for insuring maximum machine and lubricant life is the selection of the **correct** oil. This process includes choosing the correct base oil, the correct viscosity, and the correct additives for the application. Next in importance is keeping the oil **clean** and **dry**. **Particulate** and **water contamination** can have devastating effects on machine and lubricant life.

The primary source of **particulate** contamination in lubricants is ambient dust and dirt. While the composition can vary, in general dust and dirt will contain materials such as silicon oxides and aluminum oxides. Elemental indicators of dirt ingress would be silicon (Si), aluminum (Al), and in some cases calcium (Ca) and magnesium (Mg). To illustrate the effect these materials can have on lubricant-wetted components, it should be noted that these materials are the same as those used as the abrasive media in sandpaper. These particles are typically much harder than materials used in most machinery components.

If a contaminant particle is larger than the clearance between two machine surfaces, the particle will grind against them, removing metal from the machine surfaces in a process called **abrasive wear**. The resultant wear particles can cause a chain reaction by increasing the total number of particulates in the lubricant. Additionally, this newly generated abrasive wear material can get broken into smaller particles and become harder due to the process of work-hardening. These more numerous and harder particles combine with the original solid contaminants to increase the amount of abrasive material that is in the lubricant.

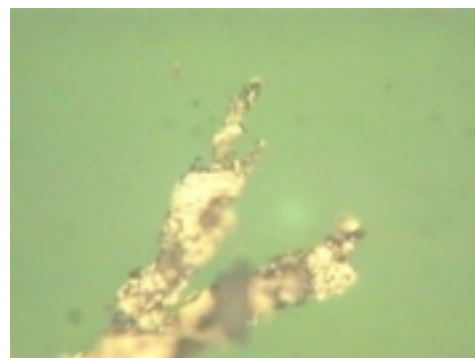
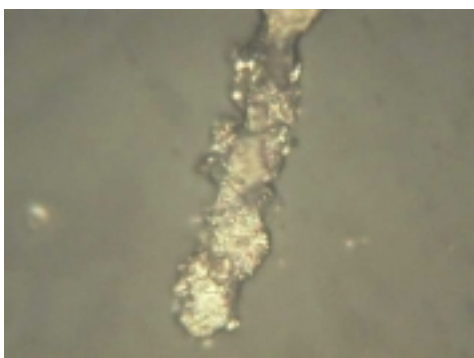
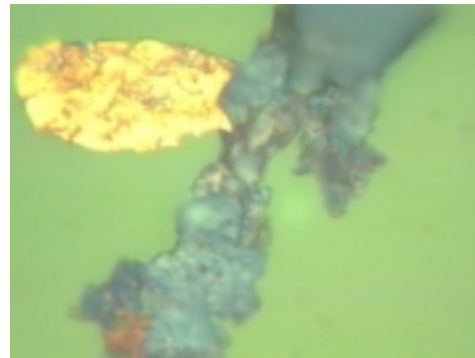
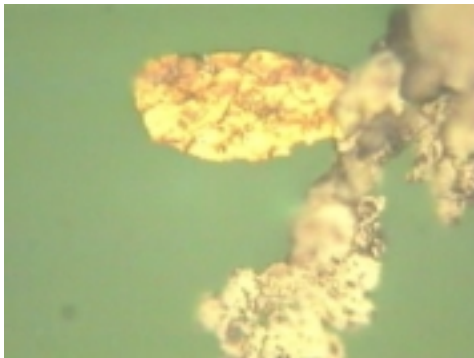
Under conditions of high velocity or high pressure or both, small particles can impinge on a machine surface and result in **erosive wear**. In this case, particles can be much smaller than the machine clearances and still cause extensive damage due to the velocities and pressures involved. Particles generated during erosive wear also add to the overall contamination of the system and further increase machine wear. Erosive wear most commonly occurs in hydraulic systems that contain devices such as servo and proportional valves.

**Adhesive wear** takes place under conditions of excessive load, low speed, or reduced fluid viscosity, occurring when the fluid-film thickness is reduced to the point where metal-to-metal contact occurs. When "high spots" or asperities from the opposing surfaces come into contact, they are cold-welded together. As the machine surfaces separate, the welded asperities are sheared off and become wear particles in the lubricant. Due to the cold-welding process, these adhesive wear particles are harder than their parent metal surfaces. Further cold-working, as they are broken into smaller particles, makes them even harder. They are added to the particulate load in the lubricant, compounding the abrasive and erosive wear process.

Adhesive wear is not specifically caused by solid particulates in the oil, although they can contribute to the process. **Water contamination**, however, can definitely result in adhesive wear. In elastohydrodynamic (EHD) lubrication, such as occurs in rolling element bearings, extreme pressures up to 500,000 psig can be momentarily generated at the interface between the rolling element and the bearing race. Because lubricant viscosity increases with increasing pressure, the lubricant momentarily becomes a solid, protecting the surfaces in motion. Water, however, does not change viscosity (with increasing pressure) over its entire liquid-state temperature range. This can have the effect of reducing the viscosity of the lubricant, both overall in cases of bulk contamination or in localized situations. At the high pressures generated in a rolling element bearing or between heavily loaded gear teeth, such a viscosity drop can allow surfaces to come in contact and adhesive wear will occur.

If contaminant particles or wear debris is trapped between two machine surfaces, they can cause dents and cracks in the surfaces. Even if the oil is cleaned afterwards, the repeated loading from normal machine operation can cause the cracks to spread under the surface. Surface and subsurface cracks may be microscopic initially, but as the metal fatigues, the surface will eventually fail and a large spall will form in a process called **fatigue wear**. As with all wear modes, fatigue wear also releases wear particles into the lubricant. While still attached to the parent surface, these particles are cold-worked during the fatigue wear process and, once again, are harder than their parent surfaces.

Without a contamination control system in place, all of these processes can build upon each other in a progressive manner. The result is an exponential increase in the wear rate, resulting in rapid machine failure once the wear mode has been initiated. Figure 1 shows various wear particles under magnification.



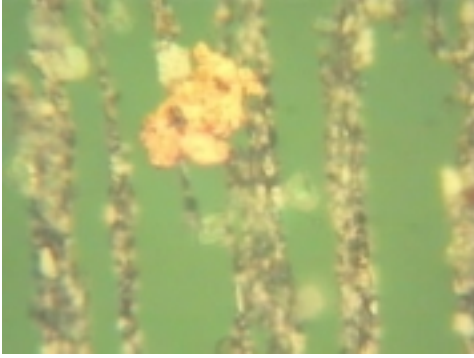


Figure 1 – Examples of various wear particles under magnification (ferrography).

Most of the discussion to this point has revolved around the issue of solid particulate contamination and its chain reaction effects on **machine condition** with a slight mention of water-induced problems. This is not to imply that moisture contamination should not be aggressively controlled, as it can be just as devastating on machine condition as particulate contamination. Its effects may not be as immediately noticeable, but it has a more widespread interaction with machine surface properties and lubricant properties. The overall effects of moisture contamination can be more systemic than particulate contamination.

Moisture contamination can have numerous direct effects on machine condition. The most obvious effect of water is to cause **rust and corrosion** of iron and steel surfaces in a process called **corrosive wear**. Most lubricants are somewhat acidic by nature, and the addition of certain additives can make them more acidic. The normal degradation process also tends to increase a lubricant's acidity. Water combines with the acids in the oil to increase the corrosive potential and increase the attack on ferrous and nonferrous metals. Corrosive wear results in the removal of metal from the component surface, typically in the form of ferrous oxides. Ferrous oxides, or rust particles, are abrasive; and, in conjunction with other wear debris and abrasive particles, they can expose fresh base metal for further corrosion.

The **viscosity of water** is lower than virtually any lubricant applied and its viscosity does not increase with increasing pressure, as a lubricant's will. Therefore, water adversely affects machine condition by causing **insufficient fluid-film strength** and allowing machine components to come into contact. This effect can occur regardless of whether the aqueous contamination is in the form of free water or if it is emulsified with the oil. The resulting emulsion will have a viscosity higher than water but lower than the oil, and proper fluid-film strength will not be achieved.

If water is present in a lubricant under conditions of low pressure, it can form a water vapor bubble. When the water vapor bubble is then exposed to a high-pressure region of the machine, it will implode and condense back to the liquid phase in a process called **cavitation**. The implosion results in the formation of microjets, which impact the metal surface at high velocity and force and also bring dissolved oxygen to the grain boundaries of the metal. In the milliseconds that it takes for cavitation to occur, the microjets cause disintegration of the metal while the oxygen results in corrosive chemical attack of the metal grain boundaries. The initial effects, microscopic in nature, are called micro-pitting. As the damaged surface experiences further cavitation and fatigue, the pit enlarges until a spall is formed as described earlier in the discussion about fatigue wear. Cavitation can occur with air bubbles as well as water vapor bubbles. Water contamination increases the lubricant's ability to entrain air, which in turn, increases the potential for cavitation-induced wear.

When water is present in a lubricant, some of it will decompose to form hydrogen and oxygen. Hydrogen can interact with the metal surfaces to cause **hydrogen embrittlement**. As the name implies, this process causes the metal to become more brittle or lose its ductility, rendering the metal more prone to fatigue wear.

### Lubricant Condition

While particulate contamination has a more direct influence on machine condition, water contamination has a more direct influence on lubricant condition. Independently, either type of contaminant can degrade both the machine and lubricant conditions. Together, they can feed off each other to greatly increase the degradation rates of both the machine and the lubricant.

One of the more critical lubricant condition properties is the **oxidation** that has occurred, as all lubricants will oxidize over time. The oxidation process is accelerated in the presence of elevated temperatures, water content, metal catalysts, and solid contaminants. Beginning with the formation of organic peroxides, further oxidation results in the formation of alcohols, aldehydes, ketones, and organic acids. These products can be further oxidized to form high molecular weight polymers that are insoluble in oil. These polymers manifest themselves as sludges, varnishes, and gums, and impair normal equipment operation. Organic acids formed as a result of oxidation are corrosive to many machine component metals and thus increase the rate of corrosive wear. Additionally, with oxidation, lubricants increase in viscosity, further compounding the oxidation rate by increasing the fluid friction and, therefore, the heat input to the oxidation process.

Solid contaminants, whether they are dirt or wear-generated debris, will increase the oxidation rate of the lubricant, because these materials contain metals that catalyze the oxidation process. The presence of these metals alone can cause oxidation rates to increase to five times the normal rate, while the presence of water can increase the oxidation rate ten times. **Combined, water and metal catalysts can increase the oxidation rate fifty times or more.** Although the presence of heat and air are not typically considered contaminants, excessive heat can also increase the oxidation rate. A rule of thumb for the rate of heat-induced oxidation is that for every 10 degrees C (18 degrees F) above 60 °C (140 °F) the oxidation rate doubles. As the amount of air in lubricant increases, the oxidation rate increases at a similar rate. Entrained air can result from excessive agitation in the lubricating system, the presence of water, or too much or too little antifoam additive.

The combined presence of water, metals, heat, and air can cause a lubricant to oxidize rapidly as the following example demonstrates. A small steam turbine, operating in a facility and using synthetic turbine oil, was known to have high water and temperature contamination due to unreliable seals. It was also known to suffer from pipe-strain-induced misalignment. The presence of excessive air or metal catalysts was not known. In this case the lubricant became severely oxidized resulting in oxidation polymers, or gels, in as little as one to three months of continuous operation.

Contaminants, notably particulates and water, also cause **additive depletion**. Additives are chemicals used in lubricants to add or enhance certain properties to the base oil. These materials vary greatly in their function and their concentration in the lubricant. Many of these additives are polar in nature, meaning that one end of the molecule will be positively charged and the other negatively charged. This characteristic gives them an affinity for solid surfaces such as metal machine components, metal contaminants, and metal wear debris. If contaminant metals are present in the lubricant, the additives may adhere to these particles by design for removal in a filter or reservoir. During excessively high contaminant load, this mechanism can rapidly deplete the available additives. If excessive wear metals are present, certain additives may preferentially adhere to these metal surfaces rather than adhering to and protecting the remaining metal surfaces as intended.

Water also promotes accelerated additive depletion because water is also a polar compound. Therefore, it has a natural affinity for the additives and will interfere with their intended function. Additionally, some additives (and certain synthetic lubricants) have poor **hydrolytic stability**, meaning that they have poor resistance to chemical degradation and are rapidly depleted in the presence of water.

The combined effects of solid and moisture contamination pack a one-two punch that no machine and lubricant can endure for very long without a suitably designed contamination control system in place. A contamination control system must be appropriate for the application and must also pack its own one-two punch that prevents the ingress of contaminants and successfully removes any contaminants that are present.

## What Is Ideal Cleanliness?

A question often asked is, "What is the ideal cleanliness for a lubricant?" Ideally, a lubricant would not contain **any** particles, water, or other contaminants. In industries that require sterile or clean rooms, it is possible that any lubricants used could meet that ideal cleanliness where the nature of the process justifies the cost of extreme contamination control. If ideal cleanliness could be achieved, lubricants and the machines they protect would be able to attain maximum life expectancy (given no other mechanical problems). In reality, this is an approachable but, mostly unobtainable, goal. For any industry, the question has to be, "What is the practical and economically justifiable cleanliness required for each application?"

## What is the Practical Cleanliness for an Application?

The engineering approach to lubricant cleanliness provides a balance of the various factors involved, including:

- Machine type
- Service application
- Machine component clearances
- Lubricant type
- Lubricating system type
- Lubricating system volume and flowrate
- Operating duty
- Operating environment
  - Types of potential contaminants
  - Likelihood of contamination
- Machine criticality
- Lubricant storage and handling practices
- Mean time between failure (Repair history)
- Repair costs
- Lost production costs
- Lubricant purchase costs
- Lubricant change frequencies and volumes
- Lubricant disposal costs
- Contamination control system capital costs and operating expenses
- Health, Safety, and Environmental considerations
- Initial lubricant particle counts, water concentration, and ingress rates

The goal is to implement contamination control systems and practices that maximize machine and lubricant life, while minimizing capital and operating expenses to provide the greatest overall value. For example, some machines may experience a high dirt ingress rate due to the operating environment and ineffective shaft seals. A typical solution would be to install finer cartridge-type filters to improve the lubricant cleanliness. This could potentially result in filter

change costs that far exceed the benefit of cleaner oil based on the machine history. A better solution would be to improve the design or maintenance of the shaft seals to reduce ingress and use automatic, self-cleaning fine filtration devices to improve and reduce the cost of contaminant removal. Obtaining a full understanding of the situation will enhance the likelihood of achieving an optimum solution.

**Particulates**

While each application will be unique, some general guidelines for lubricant cleanliness have been established for different types of machines or machine components. Typical target ISO cleanliness codes for various machines and machine components are listed in Table 1. Keep in mind that these are typical targets. Factors that could lead to cleaner oil requirements include machine criticality, severe duty, expected service life of more than seven years, or if system failure could cause safety or environmental issues. The more of these issues that apply, the cleaner the lubricant should be. Systems that have higher operating viscosities may need to operate at somewhat less stringent cleanliness targets due to the difficulty of filtering higher viscosity fluid.

Machine/Component	Typical Target ISO Cleanliness Code (ISO 4406:1999)
Servo valve	13/12/10
Proportional valve	14/13/11
Variable volume pump	15/14/12
Fixed piston pump	16/15/12
Vane pump	16/15/12
Gear pump	16/15/12
Ball bearing	14/13/11
Roller bearing	15/14/12
Journal bearing	16/15/12
Industrial gearbox	16/15/12
Turbine	17/15/12
Diesel engine	17/16/14
Paper machine	18/16/13

Table 1 – Machine/Component Target ISO Cleanliness Codes

An understanding of what these codes mean requires a discussion of the structure and nomenclature of the codes. The structure can be broken down as follows:

**16 / 15 / 12**

The first number, “16”, is the range code number that corresponds to a range of the number of particles present in an oil that are greater than 4 microns (µm or micrometers). That count is typically based on the number of particles per milliliter (ml). The second number, “15”, is the range code number corresponding to the number of particles/ml that are greater than 6 microns and the third number corresponds to the number of particles/ml greater than 14 microns in size. It should be noted that the first range code includes the particles from both the second and third range codes. Likewise, the second range code includes the particles counted in the third range code.

The actual numbers of particles counted per milliliter in each size category (4, 6, and 14 microns) are converted to the appropriate ISO Code via the chart in Table 2.

ISO/Range Code	Min particles /ml	Max particles /ml
1	0	0.02

2	0.02	0.04
3	0.04	0.08
4	0.08	0.15
5	0.15	0.3
6	0.3	0.6
7	0.6	1.3
8	1.3	2.5
9	2.5	5
10	5	10
11	10	20
12	20	40
13	40	80
14	80	160
15	160	320
16	320	640
17	640	1,300
18	1,300	2,500
19	2,500	5,000
20	5,000	10,000
21	10,000	20,000
22	20,000	40,000
23	40,000	80,000
24	80,000	160,000
25	160,000	320,000
26	320,000	640,000
27	640,000	1,300,000
28	1,300,000	2,500,000
29	2,500,000	5,000,000
30	5,000,000	10,000,000

Table 2 – ISO Cleanliness Codes

For example, if a particle counter determined that there were 501 particles/ml greater than 4 microns, the corresponding ISO code would be 16. If 199 particles/ml were greater than 6 microns, the corresponding ISO code would be 15. Finally, if the counter determined that 27 particles/ml were greater than 14 microns, then the corresponding ISO code would be 12. The overall cleanliness of the lubricant would be reported as 16/15/12. Most particle counters do this conversion automatically. The following characteristics should be noted:

- The number of particles/ml will always correspond to the same ISO code independent of the particle size being measured.
- The overall ISO code structure – XX/YY/ZZ – will always correspond to the particle counts at the sizes:
  - XX – greater than 4 microns
  - YY – greater than 6 microns
  - ZZ – greater than 14 microns
- Each ISO code increase represents roughly a doubling of the particle count
- However, an increase of only 1 particle/ml at a particular size can also give the appearance by the ISO code that the oil is twice as dirty

It should be noted that the ISO Cleanliness Code was revised in 1999. The earlier code used only two range values corresponding to particles greater than 5 microns and 15 microns. This would be reported in the following format: YY/ZZ. Additionally, some companies also used a range code for particles greater than 2 microns, and it would be reported similarly to the current code structure with the particle sizes corresponding to 2, 5, and 15 microns as opposed to the new 4, 6, and 14 microns. This change was due to the phasing out of AC Fine Test Dust (ACFTD) as the test method and replacing it with Medium Test Dust (MTD) and to improvements in the test procedure. There is no net effect on filter performance and minimal effect on how particle counts are reported with this change. The new reporting standard may be referred to as ISO 4406:1999 or ISO 4406 (MTD). The previous standard may be referred to as ISO 4406 (ACFTD). Results reported as a two “digit” code could be assumed to be the older standard at 5 and 15 microns. If results are reported as a three “digit” code it is assumed to be the new standard at 4, 6, and 14 microns. Many labs will report the appropriate sizes to avoid confusion.

Users should be aware of this as particle counters calibrated to the old standard are still widely used and will be for some time. Particle counters calibrated to the new standard are available and will become more common with time. Particle counters that are calibrated and report to the new standard will meet the ISO 11171 calibration standard.

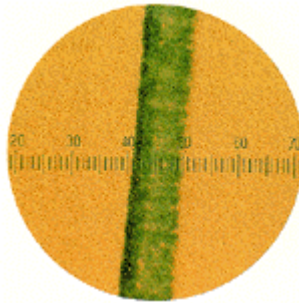
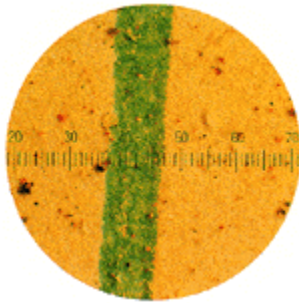


Figure 2 – Oil at 19/17/14 (ISO 4406:ACFTD)    Figure 3 – Oil at 12/10/7 (ISO 4406:ACFTD)

**Moisture**

Typical target water limits are not as well-established as are those for particulates. The interaction of water with lubricant film strength and chemical interactions with the lubricant additives and machine surfaces can be devastating. Water content in a lubricant can exist in three forms: free, emulsified, and dissolved. Free and emulsified water pose more of a problem than dissolved water, and maintaining content well below the saturation point of the lubricant will minimize its harmful effects.

Saturation point is dependent on the particular nature of the lubricant and the oil temperature. The higher the oil temperature, the more water it can hold in the relatively harmless dissolved state. However, caution must be noted in applications where operating or ambient temperatures can vary widely. The saturation point of the bulk oil in the reservoir may be significantly different than that at various points in the lubricating system and at different times of the day or year (due to temperature variation).

Experience indicates that many industrial machines utilizing rust and oxidation inhibited circulating oils, or gear oils can be expected to have water concentrations below 100 ppm. In a proactive maintenance program, typical water limits and appropriate responses can be summarized in Table 3.

Water Concentration, ppm	Status	Action
100 – 300	Alert	Check seals, breathers, coolers, etc., for ingress sources; watch trend
300 – 800	Danger	Aggressively investigate and correct source of ingress and implement effective water removal activities
800+	Extreme Danger	Immediate action is required to eliminate ingress and effect removal of water to minimize damage to machine and lubricant

Table 3 – General Water Concentration Limits

These limits are very general in nature. Systems that involve rolling element bearings, extremely low temperatures, certain synthetics, exposure to refrigerants, and transformer oils will typically require very low water content for maximum life. For those where the lubricant is exposed to combustion processes, a higher allowable water content is typical due to produced water. These lubricants are designed to emulsify the water until it can be driven off by the heat of combustion.



It should be noted that many tests for water cannot accurately detect content below 1000 ppm. The most effective way to accurately determine low water content is the Karl Fischer Co-Distillation method. This method distills the free, emulsified, and dissolved water from the lubricant, which is then titrated using the Karl Fischer reagents to determine the water content. In contrast, the Crackle Test and Fourier Transform Infrared Spectroscopy (FT-IR) methods can only detect free water accurately down to about 1000 ppm. The Crackle Test has the further limitation in that it is only a pass/fail test that cannot quantify the amount of water present.

## Advantages of Clean and Dry Lubricants

Maintaining lubricants at minimal particle and water concentrations maximizes both machine and lubricant life. For example, a lubricant operating at a typical ISO Cleanliness Code of 21/18/15 could achieve a machine life improvement of 1.5 to 2 times if it was cleaned and maintained to a target ISO Cleanliness Code of 18/15/12. This obviously depends on the specifics of the application and the type of machine components involved, but serves to illustrate the point.

In some applications, maintaining water content in a lubricant at 1,000 ppm can result in a 75% reduction in component life versus operating at a water content of 100 ppm, if all other factors remain constant. Combining the effects of cleaner and drier lubricants provides a cumulative improvement in machine component life.

Maintaining clean and dry lubricants requires a continual effort utilizing a two-pronged approach: **ingression prevention** and **contaminant removal**. Most contamination control efforts only focus on removing contaminants after they have entered the lubricant. Preventing the ingression of particulates, water, and other contaminants into a lubricant is the most effective, and often least utilized, method of controlling contamination. Combining the two approaches will maximize machine and lubricant life and minimize contamination control costs.

## Ingression Prevention

Ingression prevention involves minimizing the likelihood of contaminating the lubricant from all potential external sources before the lubricant is introduced into the machine and while it is in service. This involves numerous contamination sources that should be addressed such as:

- Lubricant manufacture, blending, storage, shipping, and handling
- Facility storage and handling practices
- Machine manufacture and repair practices
- Lubricating system design, commissioning, and maintenance
- Machine designs to minimize ingression

### Lubricant Supplier Efforts

Most suppliers take some degree of effort to produce and deliver lubricants that are clean and dry. Some will guarantee a certain ISO Cleanliness Code while others will offer products in filtered and non-filtered states. They also make an effort to insure that containers are clean and refillable compartments on transportation carriers are properly cleaned and flushed. The lubricant user should check with their supplier to determine what efforts and capabilities the supplier takes to insure lubricant cleanliness. However, periodic testing of new lubricants often reveals that they can be dirtier and contain more water than the target values for a specific application. One should never assume that a freshly opened container of new lubricant is satisfactorily clean and dry unless the supplier has demonstrated their procedures for insuring cleanliness. Periodic sampling of the lubricant should be performed to certify the effectiveness of these procedures.

### Facility Storage and Handling Efforts

Even if a lubricant supplier delivered all its products in pristine condition, many facilities do not implement storage and handling practices that insure the integrity of the lubricant over the storage life. Ideally, lubricants should be kept in a sheltered, climate-controlled, minimal-dust facility. Unfortunately, this level of protection is often not achievable or practical.

The most commonly used container for lubricants in many facilities is the steel drum. When not stored in a climate-controlled area, a new steel drum with factory sealed bung covers can still allow the entry of significant amounts of dirt and water as it breathes with changes in ambient temperature. One of the more effective means of insuring that lubricants are kept clean during storage and handling is to use an appropriate sized container for each application to minimize the length of time that a container is stored in an unsealed condition. Container options include:

- Bulk tanks greater than 2000 gallons
- Individual bulk containers (IBCs) that may be plastic or stainless steel (carbon steel is not recommended) and can range from 300 to 1500 gallons
- Plastic or steel 55 gallon drums
- Plastic 5-gallon pails
- Plastic 1-quart to 2.5-gallon bottles

Properly designed and sealed containers offer significant ingress-prevention capabilities as opposed to drums. Use of drum pumps should be minimized, as they are difficult to store cleanly and can cause cross-contamination unless a dedicated pump is used for each individual product. IBCs and drums should be fitted with desiccant breathers that filter out dirt and moisture as the container breathes over the course of time.

Drums in outside storage should be placed horizontally with their fill and vent bungs located at the 3 and 9 o'clock positions. This orientation prevents the collection of water on the top of the drum, and the lubricant provides a seal at the bungs to prevent dirt and water ingress. Drums that have been opened and are in use should also be stored horizontally. The fill/drain bung should be at the 6 o'clock position for filling smaller containers with the vent bung at the 12 o'clock position. Desiccant breathers can be fitted to the vent bung to prevent contamination ingress. Vent bungs from several open drums can be piped together and tied to a common desiccant breather for all drums. The vent piping used should be clean so that it does not introduce contaminants into the oil.

On-site handling practices are very important to lubricant cleanliness, as a significant cause of lubricant-related failures is the addition of the wrong oil into a system. To help minimize this concern, all lubricant containers should be clearly labeled with the specific lubricant product contained. Additionally, machine lube points should also be clearly identified such that a lubricator can compare the machine lube tag to the container label and confirm that the right lubricant is applied.

If a drum is used as a fill container for a machine, the fluid should be run through a filtration cart to clean the oil as it is introduced to the machine. Portable filter carts are available with dolly-mounted pumps and filters. Pump flow rate and filter specifications are application-specific. Again, to avoid cross-contamination, one filter cart should be used for each family of lubricants. Fewer carts can be utilized if adequate flushing practices are followed. **It should be noted that a cart used for industrial oils should never be used for internal combustion oils.**

### **Machine Manufacture and Repair Practices**

While intense efforts are undertaken to insure machines are carefully manufactured and repaired to insure reliable operation, the housekeeping conditions under which the repairs occur in an open machine can lead to a large potential for contamination. Manufacture and repairs, whether on-site or off-site, should take into consideration efforts to minimize contaminants left in the

machine. Additionally, commissioning, re-commissioning, and flushing procedures should be implemented prior to startup to remove contaminants resulting from manufacture or repair.

### **Lubricating System Design**

The design of the lubricating system can have significant impact on contaminant ingress. Reservoirs must be properly sealed against dirt and water ingress and breathers should be of a diaphragm type or desiccant breather type. Diaphragm types allow for expansion and contraction of the air space above the lubricant without any actual air exchange. Desiccant breathers do allow air exchange as a result of expansion, but filter and dry the air as it enters the reservoir. Some systems may require the use of an inert gas blanket or purge to provide a positive pressure on the reservoir to keep contaminants out. These systems also protect lubricants that are highly sensitive to oxidation by air. Oil mist systems are also useful in preventing contaminant ingress. In addition to their lubricating benefits, the oil mist provides a positive pressure purge that keeps contaminants out and replaces the air that would contribute to oxidation.

These systems must also be designed such that the pump flowrate does not result in excessive agitation of the lubricant, which can cause increased air, water, and particle entrainment in the oil. Excessive temperature increase and shearing of the lubricant can also result. All of these issues can have adverse effects on the lubricant and machine life.

### **Machine System Designs**

Machines commonly employ a variety of designs to minimize contaminant ingress. Larger machines are typically, but not necessarily, better protected against contaminants than small machines. Many small machines have traditionally used lip seals to prevent oil leakage and contaminant ingress around the shaft. However, these lip seals are not effective over the long term and more machines are now employing bearing isolators. Bearing isolators are dynamic seals that form a labyrinth that keeps the lubricant in the reservoir and the contaminants out.

Typical machinery breather vents that do not prevent moisture or dirt ingress can be replaced with desiccant breathers. Many small machines use bulb-type constant-level oilers that can allow for significant contaminant intrusion. Utilization of bulls-eye or liquid level indicators is preferred.

The practices and products identified above are examples of the efforts that can be employed to minimize contaminant ingress. It is not intended to be exhaustive and may not apply to all applications. Each situation must be evaluated individually to provide the best solution.

## **Contaminant Removal**

Ingression prevention methods can reduce the amount of contaminants in a lubricant, but are not likely to eliminate them completely. Some contaminants are generated internally, such as in a combustion application where by-products of the process (soot, water, acids, etc.) are going to be present regardless of any prevention efforts. Additionally, the operating conditions themselves can result in the generation of wear metals that are not related to a lubricant problem. Nevertheless, harmful materials are generated and must be removed from the lubricating system to insure maximum life.

A variety of tools and methods are available for contaminant removal from a lubricant. Each one has its merits in terms of capabilities and cost, and they are described below.

**Reservoir settling** simply involves allowing the lubricant sufficient space and residence time to allow particles and water, which have a higher specific gravity than the lubricant, to separate to the bottom. These contaminants can remain at the bottom of the reservoir where they will not

cause any harm or can be removed by opening a low-point drain. Periodically, a reservoir would need to be completely drained and cleaned to remove the buildup of particles, water, and sludges.

This is a relatively inexpensive and simple method of contaminant removal. However, consideration must be given to the location of suction and return lines, the use of baffles and weirs, floor slope, seals, breathers, volume, and residence time. The goal is to maximize contaminant removal using the minimum-sized reservoir at the minimum cost and to avoid any agitation of the reservoir. An improperly sized or designed reservoir can actually increase lubricant agitation, making it less likely that contaminants will separate out.

Reservoir settling is the least effective method of contaminant removal and only larger particles and free water will settle out.

**Centrifuging** is the process of spinning the lubricant at high speeds to remove contaminants that are denser than the lubricant. It essentially enhances the gravitational effect of a settling process and therefore drastically reduces the residence time required to achieve the same (or better) removal efficiency. Most solid contaminants and free water can be removed, but it is not effective for entrained gases and dissolved water. The amount of oil-water emulsion may or may not increase and certain additives (such as those in suspension) can be removed. Additives that are completely dissolved in the lubricant will not separate out.

**Vacuum dehydration** utilizes the principle that water boils at a lower temperature under vacuum conditions. These dehydrators employ vacuum pumps, large mass transfer area, and short-term exposure to moderately elevated temperatures. This enables most of the water content, including dissolved water, to be effectively removed. To improve the effectiveness of this technique, it is best to first remove the majority of the free water by settling or coalescing. Vacuum dehydrators can also remove some volatile fluids. This is one of the more effective methods of achieving very low water content.

**Air/Gas Stripping** is somewhat similar to vacuum dehydration in its operating principle and performance. The primary difference is that instead of using a vacuum pump to lower the boiling point of water, this method uses a mixing nozzle to provide intimate contact between the gas and the oil. Water-contaminated oil is exposed to short-duration elevated temperatures and is then mixed with an appropriate gas. The gas is dry relative to the water-contaminated oil and the moisture will migrate from the oil to the gas. A separation process occurs wherein water vapor is vented to the atmosphere or flare, and clean dry oil is returned to the reservoir. These devices typically employ particulate filters as well. An advantage of air/gas strippers is that a vacuum pump is not required, so maintenance efforts are reduced to filter changes and fairly reliable lube oil gear pumps.

**Filtration** is probably the most widely applied method, and most industrial applications employ a filter housing and one or more cartridge-type elements. Some filters employ a bed containing the media through which the lubricant passes. Filters can range from strainers that only remove relatively large particles to those that can remove low micron and sub-micron particles. Others are capable of removing organic acids resulting from oxidation, by employing media composed of Fuller's Earth, activated alumina, and similar materials. There are also filters designed to coalesce or absorb free water. In general, most filters will not remove lubricant additives.

A properly specified and designed filtration system can be a very effective contaminant removal tool when the characteristics of each application are known and understood. More detail regarding filter selection follows.

## How to Choose a Filter

This section will focus primarily on typically encountered cartridge-type filters. As described earlier, one of the first steps is determining how clean the lubricant should be for the particular application and then comparing this to the current system cleanliness. Taking a sample from a representative point in the lubricating system and performing a particle count can assess lubricant cleanliness. For the purposes of implementing or improving a filtration system, the ideal place to sample would be in the **supply line** to the machine. Conversely, for routine machine condition monitoring by oil analysis, the preferred sample point would be on a **drain line** after the machine.

A particle count will yield information about the ISO Cleanliness Code and should also give information on the actual number of particles at the standard size ranges. Knowledge of the machine clearances and particle sizes that are indicative of wear can yield a particle size to focus on and provide information about the particle sizes that are present in greatest quantities. In rolling element bearings, the particle size of interest might be three microns and above; in a journal bearing, the particle size of interest might be six microns and above.

Once the current and desired particle counts (or cleanliness) are known for each particle size, the required filtration ratio can be determined. This is commonly referred to as the Beta ratio ( $\beta$ ). It can be defined as the ratio of the number of particles greater than a given size ( $x \mu\text{m}$ ) in a given volume of upstream fluid to the number of particles greater than the same size ( $x \mu\text{m}$ ) in the same volume of downstream fluid. This ratio can be expressed using the formula:

$$\beta_4 = 200/100 = 2$$

Where:

4 = the particle size of interest is 4 microns

200 = the number of particles 4 microns and larger that represent the upstream or current particle count

100 = the number of particles 4 microns and larger that represent the downstream or desired particle count

2 = the resulting beta ratio,  $\beta$

Therefore, if a filter had a beta ratio of two at four microns, it would mean that half of the particles 4 microns and larger would pass through the filter. Filter performance is less commonly reported in terms of efficiency. The relationship between beta ratio and efficiency is:

$$\text{Filter efficiency} = (1 - 1 / \beta_x) \times 100\%$$

Therefore if  $\beta = 2$ , filter efficiency = 50%.

A more typical example would be:

$$\beta_4 = 1,000,000 / 5,000 = 200; \text{ Filter efficiency would be } = (1 - 1 / 200) \times 100\% = 99.5\%$$

In this case, one million upstream particles 4 microns and larger passing through a beta 200 filter would have a downstream count of 5,000 particles 4 microns and larger for a 99.5% filtration efficiency.

Better quality filters are typically described in terms of a beta ratio(s) at specific particle size(s). The micron size may also be described in terms of an **absolute rating**, which represents the diameter of the largest hard spherical particle that will pass through the filter under controlled test conditions. It is also indicative of the largest opening in the filter element.

Lower quality filters may be described in terms of a **nominal rating**. This is a somewhat arbitrary micron value that the manufacturer assigns. Sometimes filters will be specified only by micron size with no indication of the size being absolute or nominal. In general, if a filter has a micron size and beta ratio or efficiency it can be considered an absolute filter. If it only has a micron size with no beta ratio or efficiency, it should be assumed to be a nominal rating. Unless expressly specified, many equipment manufacturers that supply lubricating systems utilize nominally rated filters due to their lower cost.

Various aspects of filter element construction can play a significant role in performance and should be considered when choosing a filter.

Better filters use **filter media** that is synthetic in nature. This is most commonly a glass fiber material, although some manufacturers use one or more types of polymers. Synthetic media offer superior performance in a variety of fluids and in the presence of water. Other media, such as cotton fibers and cellulose (paper), will absorb water, causing swelling or breakdown. Some filter elements are specifically constructed or treated to absorb or coalesce limited amounts of free water. Others utilize materials such as Fuller's Earth, activated alumina, and clays for specified purposes. Various media types are dependent on the particular application, so working with a filter supplier is advised in all applications.

Filter **pore size** is another key feature and has a direct affect on the size of particles that will pass through the filter. Filters with finer micron ratings utilize smaller pore sizes; e.g., a 3-micron filter will have smaller pores than a 10-micron filter. A related aspect is the **fiber size**. Two filters rated at 5 microns absolute may appear to be equal, having equal pore sizes, but if one utilizes smaller diameter fibers, it will have greater dirt holding capacity and thus, longer life. Smaller fibers result in increased number of pores, which in turn leads to lower pressure drop and more dirt holding capacity.

Filters can vary significantly in their approach to **media support**, which typically comes in two forms: internal and external support. In some media, the fibers are bonded together using a resin, while for polymer type media the fibers may be wound while still somewhat molten. As the polymer cools to a more solid state, it becomes self-bonding. The benefits of a bonded media include resistance to deterioration from age, pressure and flow variations, temperature, and heavy dirt loading. Filters with little or no bonding will not perform as efficiently because particles can push through the relatively loose fibers. Unbonded filters can also break under high flow and pressure conditions and actually release captured particles back into the oil. This type of support is classified as internal support.

External support can include a metal core that the media is attached to and may also include support material on pleated type filters and possibly an outer wrap. Polymer-type media is self-supporting and does not require additional support on the inside or outside diameter. By whatever mechanism employed, the goal is to maintain uniform pore size and fiber integrity for maximum performance and life. Filter media that have little or no internal or external support will not provide long, reliable service.

Better filters will also employ **depth media**, which has a significant cross-section and filtration perpendicular to the media's cross-section. Depth media allows for increased dirt-holding capacity. Some filters utilize surface filtration. Here, filtration occurs only at the outer layer of the filter media. While depth media is good, some filters maintain a constant pore size across the entire cross-section of the filter media. Larger particles get captured in the outer layers of the filter element resulting in a lower effective filter life. This is due to the increasing pressure drop across the filter, falsely indicating the need for a filter change to avoid further pressure drop and potential loss of lubricant flow.

The best filters take the depth media concept one step further by employing a **pore-size gradient** across the depth of the media. Larger pore sizes will be located at the outer edge of the filter with

progressively smaller pore sizes as the oil flows to the inner part of the filter. This method traps larger particles on the outer edge of the filter and progressively smaller particles are captured towards the interior. The pore-size gradient design provides the maximum filter efficiency and life for a filter.

Additionally, many filters employ a **pleated element** design that provides significantly more filtration surface area for the relatively same element diameter. The design and arrangement of the **filter housing(s)** is also important. Any filter element can handle only a specific flow rate to insure proper residence time through the media for effective cleaning and minimal pressure drop. Depending on the specifics of the application, the housing may be designed to handle one or numerous filter elements. These elements can be stacked and arranged to maximize the number in the housing. Some of the factors affecting housing design include:

- Lubricant viscosity
- Lubricant flowrate
- Particulate ingress/generation rate
- Desired cleanliness
- Desired clean and dirty pressure drop
- Filter housing cost

Filter housings may be installed as simplex, duplex, or multiplex systems. A simplex system is one filter housing in the lubricating system and is typically installed on less-critical systems where the opportunity for element change is abundant. More critical systems utilize duplex systems where the two housings are installed in parallel. Coordinated valve switching allows filter elements to be replaced without any downtime or loss of lubricant flow. Multiplex systems are employed where flow rate, particulate load, and viscosity are very high.

Stainless steel should be used instead of carbon steel in all filter components that will be in contact with the lubricant. Water contamination is always a possibility and the filtration effort should not be complicated by the addition of rust to the system. For cases where a high degree of cleanliness is required and contaminant load is high, it may be necessary to employ one set of coarse filters and another set of fine filters. The upstream coarse set removes the bulk of large particles, allowing the smaller particles to pass through. Downstream, the fine set “polishes” the oil without undue load from larger particles. Another option in high contaminant applications is to use non-cartridge, automatic cleaning filter units. These typically have a stainless steel filter mesh with a mechanized wiper mechanism and quick opening valve. The wiper sweeps the metal screen of particles and the quick opening valve automatically purges the sludge into a suitable container along with a small amount of oil. This approach may not provide fluid that is as clean as with cartridges, but it is a good method of keeping high-dirt ingress systems a little cleaner.

In summary, better cartridge filter designs will be those that have the following characteristics:

- Synthetic media
- Optimum pore size
- Minimal fiber size
- Internally supported fibers
- Externally supported fibers
- Depth media
- Decreasing pore size gradient
- Pleated element structure
- Appropriate housing design for the application

## **When to Change the Filter**

In most cases, filters will be supplied with pressure drop indicators and recommendations from the manufacturer regarding the pressure drop at which a filter should be changed. These

indicators can be a local, visual indicator or can have a signal back to an annunciator in a control room. In duplex or multiplex systems, automatic switching between the online and offline filters can also be employed. One danger here is that the flow gets switched but the dirty element is never replaced so periodic manual inspection should be performed.

Maximum pressure drop is the typical indicator of when to change the filter. However, if only pressure-drop is monitored, some reasons to change the filter may be missed. In some systems, the pressure drop can increase and the filter can rupture. Once ruptured, the pressure-drop returns to normal or near normal and if the event is not observed or recorded, dirty fluid could be circulating when everything appears normal.

This can be alleviated if the lubricant undergoes routine sampling and analysis, including particle count, to monitor the cleanliness of the fluid. An increase of one ISO range code in any of the particle sizes above the target cleanliness should be a cause for caution or alert, and investigation may be needed to ascertain the cause of the increase. This may be due to increased ingress, filter failure, or a wear mechanism. A re-sample or sample collected from another location may also be required for corroboration. Evaluation of other routine tests may be required as well as additional diagnostic tests. Any actions will be dependent on these investigations.

An increase of two ISO range codes in any of the particle sizes above the target cleanliness should be a cause for a critical or danger indication. In this case, immediate investigation and action is necessary to prevent any excessive wear from occurring for any extensive time.

## **Weather Events and Lubricant Cleanliness**

When thinking about contamination and ingress prevention, most of the focus is geared towards common local events. Many facilities are outdoors and a certain amount of airborne contaminants should be expected. Arid areas of the western U.S. and other countries can expect occasional localized dust storms. But what about areas that don't typically experience dust storms? Are there weather events that can impact lubricant cleanliness in relatively "clean" geographic locations?

Geologic and weather events can place a large amount of particulates into the atmosphere. While most of these tend to fall out in the relatively local region of the event source, significant amounts of particles can be carried around the world and settle out anywhere. Some of these geologic and weather events over the past few decades have included volcanoes, forest fires, and dust storms from the world's largest deserts. Specifically, Mount Pinatubo in the Philippines released a particulate cloud that surrounded the globe and forest fires in Mexico in the 1990s obscured sunshine over Texas. Periodic dust storms from the Gobi and Sahara deserts can devastate those areas and studies have indicated that dust clouds from these storms occasionally cross the Pacific and Atlantic oceans, respectively, and can impact North America. A 2001 Sahara dust storm had noticeable effects in the Caribbean and in south and central Texas.

No studies are known about the direct effects of these events on lubricant cleanliness and machine condition. However, a study was made of the April – May 1998 Gobi Desert dust storm that identifies the potential. [[The Asian Dust Events of April 1998](#)] Spring windstorms in the Gobi Desert of Mongolia produce well-known dust storms in eastern Asia and the effects are often experienced in portions of China, Korea, and Japan. The composition of the dust particles has been identified as containing aluminum, silicon, calcium, iron, and titanium. These elements are known crustal elements and are also commonly identified as dirt in used oil analysis. Particle sizes vary greatly and can be carried to high altitudes. Those greater than ten microns tend to settle within one day. Therefore, the effect of the larger particles could be expected to be more of a local or regional factor.



Most of the particles that remain aloft for more than one day are in the 1 to 10 micron range with a median particle size of two to three microns. Dissipation of the dust clouds can take anywhere from five days to three weeks. Under certain conditions, these Gobi Desert dust clouds can cross the Pacific and travel over North America. In 1998, Gobi Desert dust hit the North American West Coast five days after the storm began. The dust cloud was detected throughout the Pacific Northwest and extended eventually to northern Arizona and Minnesota before finally dissipating.

What do these weather and geologic events mean for machinery operators? The effects of particulate contamination are well documented. Larger particle sizes and the abrasive nature of their constituent elements documented in this dust cloud can definitely cause machine wear. Depending on the application, the smaller particles may not be as much of a concern, but a large influx of smaller particles can still have detrimental effects. Many of the recommended actions are those previously discussed for general contamination control. Actions to consider:

- Monitor lubricant cleanliness more frequently during periods of weather and geologic events known to release and spread particulates.
- Implement or check effectiveness of best storage and handling practices.
- Use breathers and shaft seals to help keep contaminant ingress to a minimum.
- Transfer lubricants from storage to a machine using a filter cart with fine filtration elements installed.
  - 2 micron and  $\beta = 200$  or better is recommended
- Monitor particle counts on routinely tested sample points.
- Collect and analyze samples from storage facilities specifically for particle counts.
- Collect and analyze samples from a representative number of machines that are not on routine oil analysis, specifically for particle counts.
- Specific particle sizes to look for would be the 2 and 5 or 4 and 6 micron size depending on the particular ISO calibration standard of the particle counter.
- A sign of particle concentration increase should result in efforts to purify the lubricant.

## **Considerations for Air & Fuel Filters ... not Just Oil**

What about machines that utilize air and fuel filters? These devices simply represent another ingress point for particles. If the air or fuel system can enter the lubricant system, these devices should also have particle removal methods identical to that of the oil filters. The capabilities of air and fuel filters to remove fine particles are beyond the scope of this discussion, but are mentioned for the user's consideration.

Some desiccant breathers for storage tanks and machine reservoirs can filter airborne particulates down to 1 micron.

Hopefully, a better understanding of the adverse effects of contamination on machine and lubricant condition will give the reader an increased appreciation for contamination control. Additionally, the information supplied here should give the user an idea of the information required to implement contamination control efforts. Finally, an effort to keep machine lubricants clean, dry, and cool is one of the more cost-effective approaches to maximum machine and lubricant life.