Sustainable contamination control in hydraulic applications

By SKF in partnership with Noria Corporation

The lubricating fluid of a hydraulic system serves many functions beyond its base purpose of energy transference; the fluid must act as a lubricant, a sealant, a means of heat diffusion, and it must, above all, guarantee machine power, efficiency, and longevity through the reduction of component wear.

While many of us are aware that the majority of hydraulic equipment failures can be traced back to contamination problems, the path to solving these problems is often more difficult to follow. Controlling contamination requires a multi-faceted approach and a clear understanding of the major contaminant types, sources, and their effects.

In this guide, we will explore contamination in the context of hydraulic equipment. We will discuss how proactive contamination control techniques and tools can help you increase hydraulic asset service life and efficiency, decrease the incidence of failure, and lower total cost of ownership. Maintaining highly clean hydraulic oil in your machines is the key to unlocking these benefits. When it is kept clean, cool, and dry, the service life of hydraulic oil itself can also be extended significantly, decreasing oil consumption, requiring fewer drain and fill procedures, and lowering the carbon footprint of operations.

Contaminant types

Particles

Particle contamination is a major catalyst of machine failure. The primary danger of particle contamination lies in the propensity of particles to cause rapid machine wear, but these same particles can also accelerate lubricant degradation and cause harm in other ways as well.

Particle contamination can consist of dirt, wear debris, and other particles that become suspended in oil (filter fibers, pipe scale, etc.). Particles are characterized not only by their material but also by size, shape (angularity), and hardness. While different particles cause different problems, all contribute to oil degradation or component wear in one or more ways.

In fact it is the smallest particles that do the most damage.

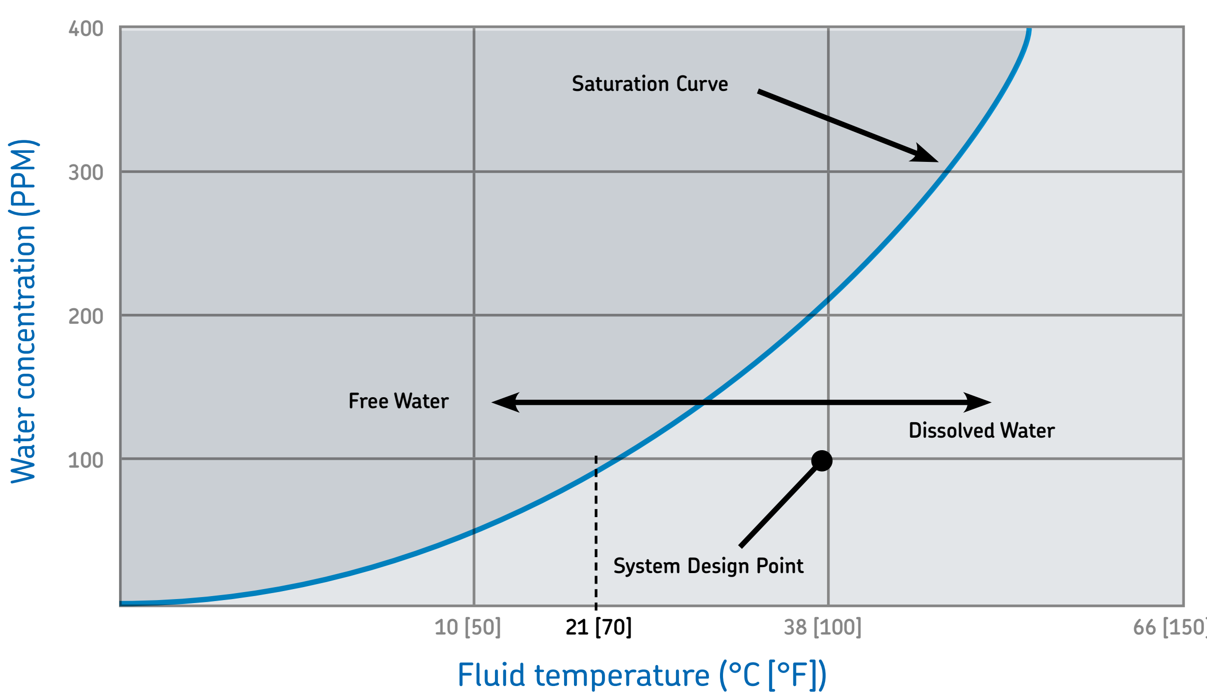


Fig 1. Example saturation curve for a typical hydraulic oil. Source: Machinery Lubrication

As larger particles are crushed into smaller ones during operation, they become more numerous and closer in size to the working clearances withing the machine.

The closer in size a particle is to those clearances, the more likely it is to enter the gap between two components or surfaces and cause abrasion or wear to both. A single 40-micron particle can theoretically be broken into 512 destructive, five-micron particles.

Moisture

Water in a lubricating oil can be present in three different forms: dissolved water, emulsified water, and free water.

Dissolved water is water that has been completely mixed with an oil; all oils contain some degree of dissolved water, typically 50 ppm in new oil. Different oils can absorb different amounts of water, and the temperature of the oil also determines how much water it can absorb. Once an oil has reached its saturation point (the maximum amount of water that an oil can dissolve), any excess water becomes emulsified water (microscopic droplets of water suspended in the oil, giving it a cloudy appearance) or free water (a separated layer of water that settles at the bottom of the oil).

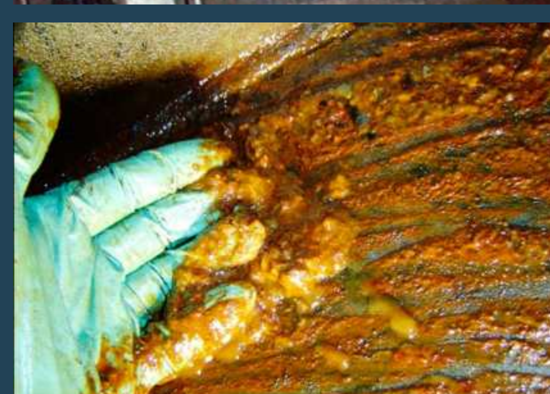
Heat

Excessive heat can be considered a contaminant, especially in hydraulic systems where high temperatures will shorten the service life of hydraulic oil by accelerating oxidation and varnish formation. When a hydraulic pump is operating at temperatures above 60 °C (140 °F), it bypasses more oil and runs slower, decreasing productivity and wasting energy. O-rings harden at higher temperatures as well, leading to leaks, contaminant ingression and further oil degradation.

What's the difference between varnish and sludge?

In technical terms, varnish is a tough, adherent oxide or carbonaceous material that coats internal machine surfaces. Often the term "varnish" is used loosely for anything that can precipitate out of oil and create a brown, sticky residue on machine surfaces. Hot surfaces or sufficient time can also cure varnish to a hard or brittle consistency in some cases.

In contrast, sludge, which is sometimes a precursor to varnish, is soft and sticky and can move about the system until finally coming to rest at sump bottoms, troughs, strainers, filters, and narrow fluid passages. Other common words for varnish and sludge include deposits, lacquer, tars, pigments, gums, and resins.



All hydraulic systems generate heat during operation, but if temperatures rise too high, it's time to check for improper pressure settings, failed heat removal systems or other possible culprits. In some cases, a simple reservoir cleaning may be all that is needed.

As a rule, hydraulic reservoirs should be cleaned at least once per year. Without an effective removal system for oil oxidation products, varnish contamination will increase until it exceeds the additive package's ability to maintain oxidative and thermal stability. The bottom and sides of the reservoir may become coated with varnish and sludge, insulating the oil instead of allowing heat to dissipate. The Arrhenius equation applied to lubricant life tells us that a 10 °C (18 °F) increase in operating oil temperature roughly doubles the rate of oil oxidation. In the dirty reservoir scenario, we have ongoing oxidation problems contributing to rising temperatures, which further accelerates oxidation. This is a deadly combination for the hydraulic oil and will end its useful life quite quickly.

Other

While particles, moisture, and heat are common, other contaminants like air, fuel, glycol, and soot may also have a significant impact on oil service life or component wear, depending on your particular application or operating environment.

The effects of contamination on hydraulic oil

The health of a hydraulic oil is directly linked to the health of its machine. When dirt is present in oil, especially dirt containing fine metal particles, it acts as a catalyst that sparks and speeds up the degradation process. Any degradation of the lubricant impacts its performance leading to increased component wear and potential failure conditions.

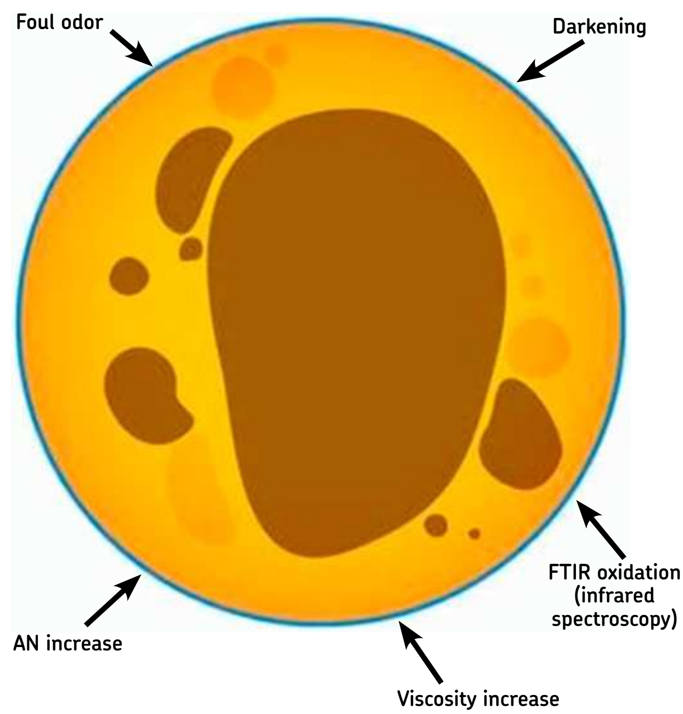


Figure 2. The five most common symptoms of oil oxidation to watch out for. Source: [Machinery Lubrication](#).

Oxidation

Oxidation of lubricants is happening all the time, but the rate of oxidation can be impacted by many factors. Air and water usually provide the source of oxygen that reacts with the oil and leads to oxidation of the lubricant, but temperature, particle contamination and other factors can also speed oxidation along.

For this reason, many tests have been developed to evaluate the oxidation state of the lubricant. Some of these tests study the potential lifetime of the lubricant while others look at the results of oxidation. Some of the most common are base number, Acid Number (AN), Fourier transform infrared (FTIR) spectroscopy or viscosity change tests. Indicators of possible oxidation problems include darkening of oil color, foul odour (like rotten eggs), increases in AN or viscosity, decreases in BN, and other, application-specific indications.

Unchecked oxidation increases the amount of nano-size contamination in lubricants. Over time, this can cause problems like varnish, increased viscosity, corrosion, rust, and other issues. To combat these issues, many hydraulic oils are formulated with antioxidant additives.

Additive depletion

Additives can help control things like oxidation and the effects of viscosity changes, but they stand to be rapidly depleted when faced with contaminants that promote oxidation, such as particles and moisture.

While antioxidants can effectively stop oxidation in its tracks, they are sacrificial. When the additive binds to free radicals formed when oil begins to oxidate, it prevents the process from propagating but some of the additive is consumed, or "sacrificed," each time.

As oil circulates in a hydraulic system, oxidation products and contaminant particles accumulate in the fluid. The majority of these particles are too small to be removed by conventional filters. And even if fresh antioxidant additives are added, old oil will gradually become too oxidized and degraded to perform. Usually, that means that equipment owners must periodically dispose of old oil and replace it with new.

But if oxidation products are removed proactively and oil is kept cool and dry through proper storage and handling, the life of hydraulic oil and even the life of its additives can be extended significantly.

Effects on hydraulic assets

Beyond the harm it causes to oil itself, contamination is detrimental to machine operation, leading to everything from reduced productivity to safety risks or even irreparable damage in hydraulic applications.

Oxidation

Oil that has oxidized does not perform well. In hydraulic applications, It can reduce oil flow, plug filters, cause valves to stick, increase friction, inhibit heat transfer and elevate operating temperature. The result is diminished hydraulic system performance. Over time, oxidation leads to the formation of varnish and sludge as well.

Figure 3. Varnish present in a hydraulic sump. If varnish is detected here, it is almost certainly present in other parts of the system as well. Source: Noria Corporation.

Varnish

Varnish deposits build up on internal metal machine surfaces. Soft deposits collect on these surfaces, especially when the surfaces are cooler than the oil, and condense, resulting in a sticky residue which collects other particles and gets worse over time.

When varnish adheres to vanes in high-performance vane pumps, the vanes can stick in the rotor slot. This can result in increased noise, decreased volumetric and mechanical efficiency with an equivalent increase in energy consumption, side plate scuffing, rotary seal damage and possibly bearing damage. The phenomenon is most obvious at low pressures when there is little centrifugal force and low fluid pressure.

In the case of piston pumps, varnish can increase piston land friction against the wear plate, leading to leakage and possible seizure. It can also block filters, leading to high use of filter cartridges and increased maintenance costs. Perhaps the most frightening impact of varnish, however, is its potential to cause silt lock.

Silt lock

The result of solid contamination, silt lock can cause abrupt machine failure. It is primarily seen in hydraulic systems and can cause components to jam or seize. Because it doesn't evolve out of machine wear, incipient silt lock is difficult to detect before failure.

Silt lock occurs when small particles enter the space between a valve's spool and bore, impacting its movement. Varnish can contribute to the problem by making these surfaces sticky, increasing the likelihood that particles will become trapped between tight clearances. This, in turn, increases the spool's static friction when the valve is actuated.

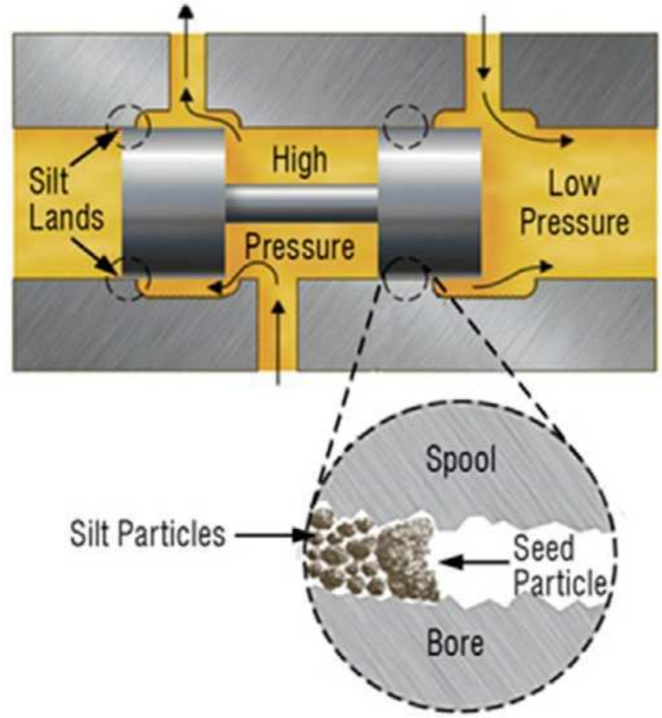


Figure 4. An illustration produced by Noria Corporation showing how silt lock can occur in a hydraulic valve. Source: Machinery Lubrication.

Silt lock is especially concerning from both a safety and production efficiency perspective because it often causes hydraulic machines to act unexpectedly, stopping suddenly or moving erratically. In an industrial manufacturing environment, this could endanger operators or stop a critical production line in its tracks. In fact, silt lock has caused major airline disasters when hydraulically-actuated control surfaces suddenly freeze in place or move unpredictably.

The key to preventing silt lock is controlling the environment in which silt lock occurs. Taking a proactive approach to both excluding and removing particle contamination is the most effective way to reduce the risk of silt lock. Monitoring the condition of oil through analysis and trending can also help you detect problems before they become catastrophic.

Changes in pump flow rates

A hydraulic system's pump is typically the hardest-worked component. As the pump wears, the flow rate of the hydraulic oil can be affected. Internal leaks, for example, decrease the flow rate of oil, which in turn reduces volumetric efficiency.

Flow rates are also influenced by fluid viscosity, which itself is impacted by oxidation, temperature and other factors. As viscosity decreases, flow rate increases, and vice versa. It is important to address problems like these when they affect oil viscosity or flow rate. If the problem lingers for too long, an entire pump overhaul or replacement pump may be required.

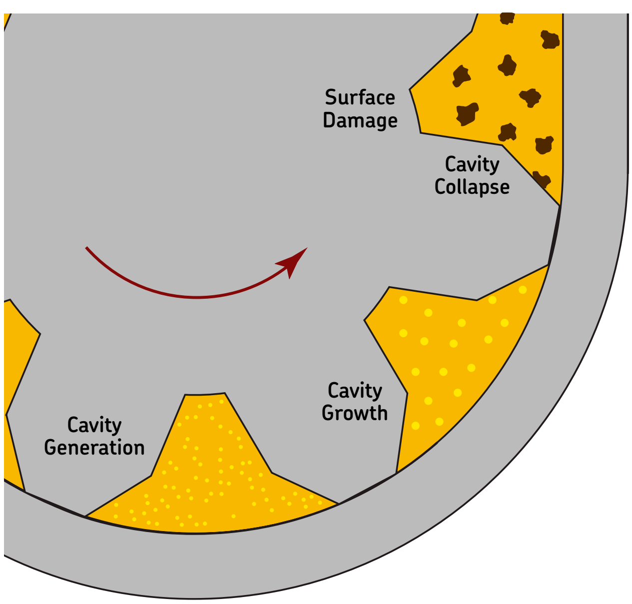


Figure 5. Cavitation can occur when there are problems with pressure settings, flow rates or other issues in system configuration. Contaminant particles can serve as the "nucleus" for cavity generation.
Source: Machinery Lubrication.

Cavitation

You may have heard the sound of cavitation in a pump before—like someone threw a handful of gravel into the hydraulic oil—but you may not realize the role contamination plays in cavitation. Cavitation starts with tiny bubbles or even some microscopic particles in hydraulic oil. Either one can serve as the nuclei or "seed" for a cavitation event. When the pressure of the fluid is reduced to a certain level, the bubbles increase rapidly in size as vapor and dissolved gasses rush to fill them. Then, when this bubble enters an area with less pressure, it collapses violently, causing local hydraulic shocks with a distinctive sound. The resulting shockwave can damage system components and degrade hydraulic oil as well.

Cavitation wear is also known as cavitation erosion, vaporous cavitation, cavitation pitting, cavitation fatigue, liquid impact erosion and wire-drawing.

Leaks

Contaminants can damage seals, which, when worn away, allow oil to leak from the hydraulic system. Not only do leaks lead to a loss of oil, but they can also be the catalyst for bigger problems and even component failure.

Figure 6. Inspecting hydraulic systems for leaks frequently is an important aspect of system maintenance, but leak reduction can also cut down on contamination ingression.

Effects on total cost of ownership

Energy consumption

Clean oil is efficient oil, and machines with clean oil don't consume as much energy as machines with contaminated oil. This improves machine optimization, and energy savings translate directly to cost savings.

Environmental Impact

In addition to reducing energy use, keeping oil clean can reduce environmental impact; degraded oil has to be replaced, and every time oil is replaced, the old oil gets thrown out. Additionally, when contaminated oil is used, leaks tend to spring up. These leaks can lead to massive amounts of oil loss. This lost oil, even if not directly soaking into the environment, must still be cleaned up and disposed of somehow. Keeping machines leak-free ensures less wasted oil and a reduced environmental impact.

Consumption of lubricants and filters

As mentioned, contaminated oil needs to be replaced more often than clean oil. Dirty oil also shortens filter life, either by breaking filters down or quickly maxing out their dirt-holding capacity.

Machine life extension through cleanliness

Using clean oil extends machine life; it's that simple. Fewer breakdowns, fewer component replacements, and enhanced machine lifetime: all this is achievable through the implementation of consistently clean oil.

Reducing the effects of contamination

To combat contamination, you must first understand how oil becomes contaminated. There are many sources of contamination to be wary of:

Identify the source

There are three ways that particles enter oil systems:

- "Built-in" particles are left behind in a machine during manufacturing or servicing.
- Ingested particles are pulled into the machine from an external source.
- Generated particles are created inside the machine during operation.

Solid particle ingression						
Built In		**Ingested**			**Generated**	
Service debris	**Manufacturing debris**	**Process**	**Atmosphere**	**Combustion**	**Surfaces**	**Oil**
Repairs	Burrs	Compressed air/gas	Breather ingestion	Blow-by	Mechanical wear	Desedimentation
PMs	Machining swarf	Pulp	Seal ingestion	Soot	Corrosive wear	Filter desorption
New filter	Weld spatter	Pulverized coal	Tank opening	Fly ash	Cavitation	Additive precipitation
New oil	Abrasives	Ore dust	Rock dust	Induction air	Exfoliation	Sludge
Dirty hose, fitting, components	Drill turnings	Aggregates	Mill scale	Contaminated fuel	Hose fibers	Oxide insoluble
Top-up containers	Filings	Cement	Quarry dust		Filter fibers	Carbonization
	Dust	Catalysts	Foundry dust		Break-in debris	Coke
	Contaminated components	Clays	Slag particles		Elastomers	
		Molecular sieves			Paint chips	
		Process chemicals				

Figure 7. This chart breaks down the primary ways that particles can enter a machine or its oil. Source: Machinery Lubrication.

Sampling locations and procedures

Sampling ports and best-practice sampling techniques allow for the retrieval of an accurate (and thus, information-rich) oil sample. Samples should be taken from turbulent areas in a machine's lubrication system; such samples are most representative of the machine's contamination levels.

Particle counting

A large aspect of oil analysis is particle counting. This is usually done using an automatic optical particle counter, which implements either a white light or a laser. In the former method, particles pass through a capillary detection zone, where their shadows are detected on a photocell. These shadows not only provide a count of particles but can also be used to detect particle sizes based on voltage fluctuations produced by the photocell. The laser method works similarly, using a photocell to detect particle count and size, but using a laser beam instead of a white light source.

Setting cleanliness targets

The only way to ensure that oil cleanliness is maintained is through routine inspection. Setting cleanliness targets gives maintenance teams a clear guideline. When the work they do is measurable, the successes or failures of the program are easier to see. Success can be repeated, and failures can be remediated.

Cleanliness Codes

Cleanliness codes, specifically those set by the International Organization for Standardization (ISO), are the most typical tool used to set cleanliness targets and key performance indicators (KPIs).

The reporting standard code for fluid cleanliness, ISO 4406:99, uses particle counting to determine an oil's level of cleanliness. This code is determined by counting particles at three different sizes: particles larger than 4 microns, particles larger than 6 microns, and particles larger than 14 microns.

Operating pressure	<103 bar (<1,500 psi)	103 - 172 bar (1,500 - 2,500 psi)	>172 bar (>2,500 psi)
Servo valve	16/14/12	15/13/11	14/12/10
Proportional valve	17/15/12	16/14/12	15/13/11
Variable volume pump	17/16/13	17/15/12	16/14/12
Cartridge valve	18/16/14	17/16/13	17/15/12
Fixed piston pump	18/16/14	17/16/13	17/15/12
Vane pump	19/17/14	18/16/14	17/16/13
Pressure/flow control valve	19/17/14	18/16/14	17/16/13
Solenoid valve	19/17/14	18/16/14	18/16/14
Gear pump	19/17/14	18/16/14	18/16/14

Figure 8. Example of target ISO Cleanliness Codes for hydraulic fluid being used with different components at various pressure ranges. Source: Machinery Lubrication.

From reactive to proactive

It is better to stop a problem before it becomes critical than it is to react to failure. Taking a proactive approach means going beyond reactive or preventive actions to focus on mitigating or eliminating known root causes of failure before even their earliest warning signs are detected.

Lubricant storage

An unorganized and dirty lubricant storage room presents opportunities for problems. Lubricants can become contaminated or get mixed up. Applying the wrong lubricant to a machine because of a storage room error is a costly mistake, but one that is easily avoided if things are organized. Lubricants in storage should also be protected from contaminant ingression while they are waiting to be put into service.

Contaminant ingression

Contaminants can get inside machines in a variety of ways, but by addressing the most common ones, it is possible to significantly cut down how much contamination is entering your machines in a given period of time.

Some of the most common sources of contaminant ingression in hydraulic systems are seals, reservoir headspace or ventilation, and maintenance activities.

Example ingression sources proportioned

Dirt (D) and water (W) ingression

100%

Contributing source		Hydraulic systems
Service debris parts and repairs	D	15%
	W	10m%
Oil changes and makeup oil	D	15%
	W	5%
Oil seals (shaft, cylinder rods, etc.)	D	30%
	W	15%
Headspace and ventilation	D	30%
	W	70%
Generated debris	D	10%
	W	0%
Cumbustion gases (blow by), coolant leaks, process steam	D	0%
	W	0%
TOTALS	D	100%
	W	100%

Figure 9. The relative impact of various contamination sources in a typical industrial hydraulic system. Source: Machinery Lubrication.

While it is not possible to eliminate all sources contaminant ingression, most can be reduced to controllable levels. Simply stated, as long as the rate of contaminant ingression is lower than the rate of contaminant removal, you will be able to maintain hydraulic oil in a clean state. It pays to start by solving contaminant ingression problems first. Keeping a gram of dirt out of a hydraulic reservoir with a desiccant breather is much cheaper and easier than removing that same gram of dirt through filtration once it has already entered the oil. Still, both aspects are needed for effective contamination control.

Desiccant breathers

As the volume of oil in a container or reservoir changes, the volume of air also changes. In this way, oil storage containers and hydraulic machines both "breathe" — pulling dust and moisture along with each "inhale." This is a significant source of contamination, but fortunately the solution is relatively simple and inexpensive. Desiccant breathers use silica gel and various filter media to protect hydraulic oil from "inhaled" water and particle contamination. They can be fitted to machines to replace OEM ventilation caps and should also be placed on lube storage containers.

While filtration is a critical tool for keeping hydraulic oil clean, we should always look for ways to avoid contaminating the oil in the first place. By cutting off sources of contamination ingression early in the lifecycle of the lubricant, we are making every subsequent contamination control activity less costly and more effective. If oil starts out cleaner, fewer filter cartridges will be expended keeping it clean, the oil itself will oxidize and degrade more slowly, and machine components will experience less wear. All of these benefits translate to savings on cost, reductions in energy and oil consumption, and more reliable hydraulic equipment. A simple desiccant breather is just the first line of defense. Once oil is in service, filtration or cleaning of some kind is needed to achieve optimal levels of cleanliness.

Factors for proper oil filter selection

Structural Integrity

Arguably the most critical factor, structural integrity relates to a filter's ability to prevent the passage of oil through an unfiltered flow path. The International Organization for Standardization (ISO) has established procedures for testing fabrication integrity, material compatibility, end load and flow fatigue. These tests can reveal defects such as improper sealing of seams and end caps or breaks in the media from high-flow conditions, as well as the effects of high temperatures on the filter element.

Dirt-holding capacity

This refers to the amount of contaminants that can be loaded onto the filter before the filter's efficiency is limited.

Pressure loss

This involves the overall differential pressure lost from the filter's placement on the system. The pressure loss will be influenced by the filter media's porosity and surface area.

Particle capture efficiency

This is the overall effectiveness of the filtration mechanisms within the filter media to extract and retain contaminants from the oil.

System/environment

The characteristics of the system and environment in which the filter will be installed must be considered, including the contamination expectations, flow rates, location, vibration, etc.

Filtration

While there are many kinds of cleaning and filtration technology available for hydraulic systems, depth-type filters designed to hold high levels of contamination are some of the most common. Selecting the right filter with optimal specifications can be difficult, but focusing on structural integrity, dirt-holding capacity, pressure loss, particle capture efficiency and any special concerns related to your specific machine and its operating environment are a good place to begin.

If used properly, conventional filters can help you achieve cleanliness targets and extend the life of your hydraulic assets. But even the best filter media cannot capture the smallest particles in oil. And in fact, it is these smallest particles at the nano scale that cause the most problems, especially in hydraulic systems.

In fact, most particles found inside in-service lubricants are very small. This is because small particles enter machines more easily than large particles and because larger particles are often crushed into smaller particles as oil circulates. For instance, for each 10-micron particle that ingresses into the oil, there may be ten 3-micron particles.

Filtration also contributes to the relative number of smaller particles present. Most filters remove particles by capturing and excluding those over a certain size. This is based on the average pore size of the filter media. Those larger particles are removed and disposed of when the filter cartridge is changed, but what about the smaller ones?

By total weight, most of these particles may be submicron (i.e., less than 1 micron in size). These include oxidation products, organic matter (soft, insoluble contaminants that can lead to sludge and varnish), and inorganic hard particles from environmental dust and wear debris. Because conventional filtration cannot remove them, these particles stay in the lubricant. Over time, they build up and degrade the lubricant, promoting further oxidation and leading to all of the problems with wear, varnish, sludge, silt lock, and others discussed above.

For some, disposing of the oil lubricant and replacing it with new is the solution, but others are starting to look at their hydraulic oil differently—as an asset to be maintained rather than a product to be consumed and replaced over and over.

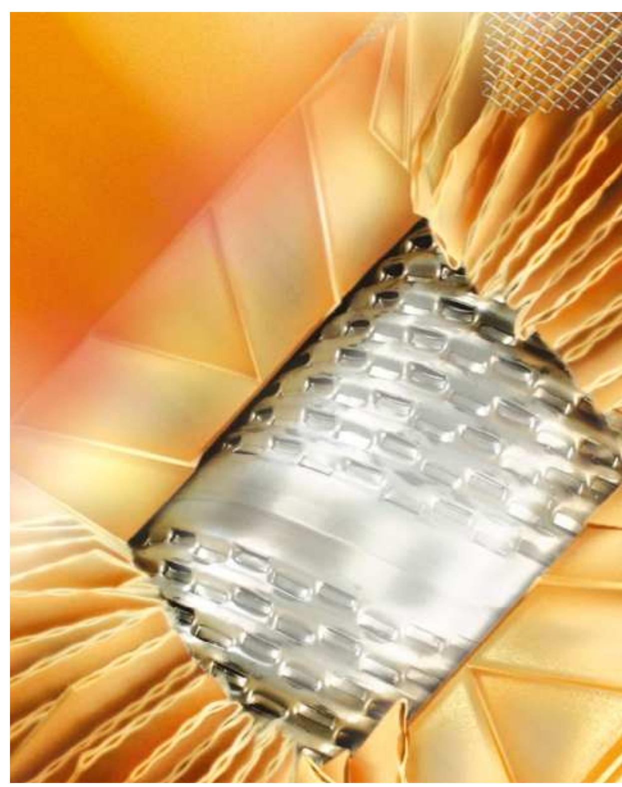
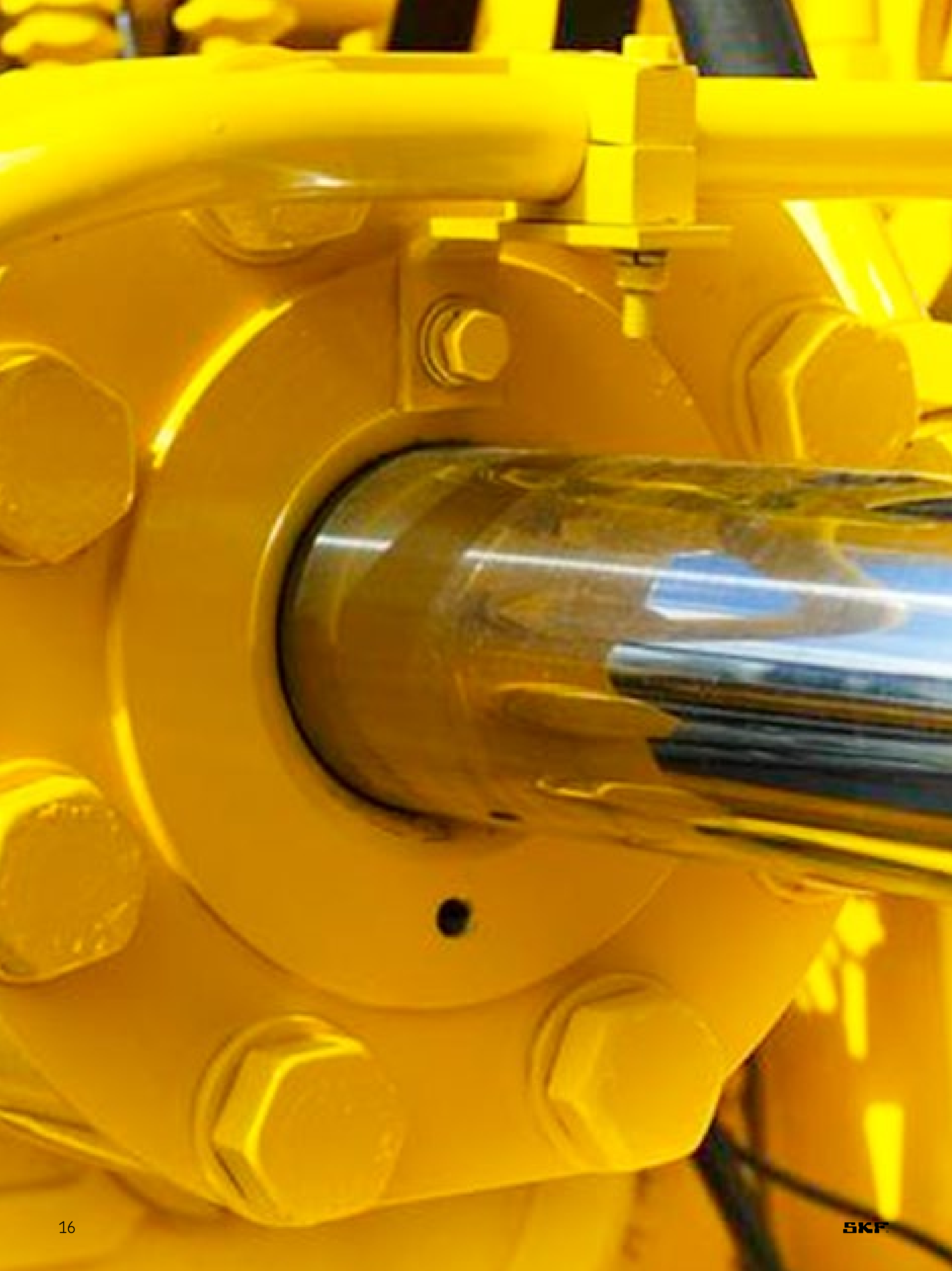


Figure 10. An close-up example of an oil filter where the filter media has been cut away. Source: Noria Corporation.



Regeneration

Oil regeneration is changing how hydraulic asset owners think about oil contamination problems. Regenerative technologies, like Double Separation Technology (DST), allow oil to be used and re-used for much longer without impacting performance. During the regeneration process, the oil is returned to a “like-new” state of cleanliness with even tiny nanoparticle contaminants, varnish, pre-varnish, and even oxidation products removed. In the best-case scenario, the same oil may be used indefinitely.

That means less oil is consumed, meaning less oil needs to be purchased, shipped, stored, and disposed of overall. Both the cost of the lubricant itself and all the associated labor, storage space, accounting, and supplier management tasks can be significantly reduced as well.

Because oil regeneration also keeps oil highly clean, hydraulic components last longer, contamination-related failures decrease, production efficiency is maintained, and the total cost of owning and maintaining the hydraulic asset decreases.

For the most critical systems, oil regeneration is a powerful tool for achieving and sustaining a proactive state of contamination control that transforms the associated costs, environmental impact and reliability of hydraulic assets.

Making sustainable improvements

No matter what approaches and tools you use to control contamination, be sure you are creating a program that can be sustained over time. Start small, cutting off sources of contamination ingression first and showing the benefits of cleaner hydraulic oil before building up to a full program. If you need help along the way, finding a solution partner with experience in hydraulic applications can simplify and speed up the process.

Building internal support for your program is also essential to a sustainable program. When speaking with management and leadership stakeholders, focus on how each activity impacts the total cost of ownership for your hydraulic assets. For those who maintain or operate machines day-to-day, noting the decrease in failure events and maintenance tasks related to oil changes, filter changes, leaks and more can help show the value of proactive contamination control.

Finally, be sure that there is a designated person responsible for your contamination control program. Fostering a cleanliness culture and keeping the program on track requires leadership and focus. Whether that leader is you or someone else on your team, be sure they understand the value of the program and how to communicate it with other stakeholders in the organization.

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