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5 Control and Management of Particle Contamination in Hydraulic Fluids

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5.1 INTRODUCTION

It has been extensively documented and widely stated that particle contamination is the number one cause of wear and failure of hydraulic components. The problem is generally more pronounced than in other types of machinery incorporating circulating systems that use similar types of oils. This heightened contaminant sensitivity is due to the high pressures and tight tolerances which are characteristic of modern hydraulic machines. Pressure is known to have a disproportionate effect on contaminant sensitivity.

Much has been learned in the past three decades about contamination control at both a laboratory research level as well as the real-world deployment of this knowledge in machinery-intensive industries. Case studies have flourished on the practical and economic benefits of maintaining hydraulic systems and fluids at extreme levels of cleanliness. Hence, the speculation is gone relating to the business case and strategies that produce savings and benefits to user organizations. For many owners of hydraulic systems the opportunities of planned cleanliness are like low-hanging fruit that is ripe for picking. This chapter summarizes this body of knowledge and the value-producing strategies needed to control particle contamination in hydraulic fluids.

5.2 CONTAMINANT SENSITIVITY AND PARTICLE-INDUCED COMPONENT FAILURE

The tribology field is replete with published studies on the damage caused by fluid-borne particles in hydraulic fluids and lubricating oils. Therefore, the focus of this chapter is not on the numerous pathways and modes of particle-induced failure, but rather on establishing and discussing some well-grounded strategies to control the damage and mitigate the risk. For those who are new to the field of tribology and machine reliability, the following is a concise summary of the four ways in which particles can rob a company of precious productivity and profits:

1. **Surface removal.** This is the product of three-body abrasion in sliding contact zones and surface-fatigue in rolling contacts. Hydraulic machines that are exposed to dense terrain dust from ambient air are at the greatest risk. These particles are harder than internal frictional surfaces causing plowing, cutting, and pitting. A hydraulic component can only tolerate so much material loss. For instance, a 20 GPM gear pump will have lost over 30% of its volumetric efficiency when just 10 g of wear metal has been generated [1]. High-pressure systems are far less tolerant to particle-induced wear than low-pressure systems. Figure 5.1 illustrates the influence of key factors that define particle contamination destructive potential in frictional zones of a hydraulic component (e.g., pumps and actuators).
2. **Restriction of oil flow and part movement.** Particles can form deposits, impede part movement and starve systems of oil. While no or limited wear may have occurred, this too can contribute to business interruption and expensive repairs. The most notorious example of this type of failure is the silt-lock of electro-hydraulic valves. These valves can become jammed due to particles lodged between the spool and bore [1].
3. **Increased consumption of lubricants and filters.** The ways in which particles can shorten lubricant service life and impair its performance are numerous. Particles accelerate additive depletion, leading to premature oil oxidation, oil-water emulsion problems, impaired corrosion protection, and poor film strength. The result is higher fluid consumption and distress to the hydraulic system. Likewise, undeterred particle ingression will lead to wastefully high filter consumption.
4. **Higher energy consumption and environmental impact.** There are many ways in which particles increase mechanical friction, impair antifriction additive performance, and decrease volumetric efficiencies in hydraulic components. The more energy and fuel that are consumed due to these losses, the more waste stream will be produced, which pollutes our atmosphere [2].

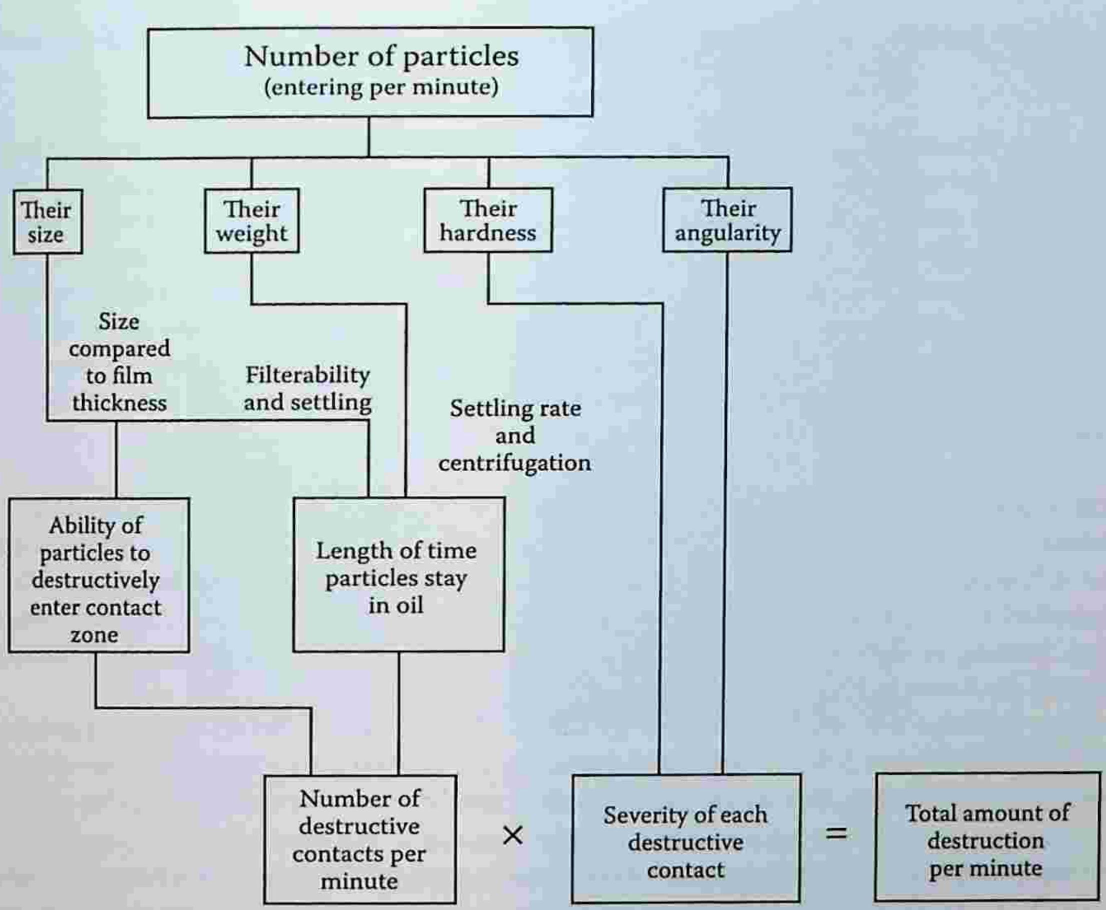


FIGURE 5.1 Particle-induced wear risk factors.

5.3 CHARACTERIZATION OF HARD PARTICLES

There is a lot to know about particles other than their size and count. The following section examines the intricacies of the physical, chemical and electrical properties that make up and characterize solid particle contamination. Knowledge of this information is useful in understanding the source of particles and their destructive potential. Not included in this discussion are soft particles and organic insolubles associated with additive precipitation, base oil oxidation, thermal degradation byproducts and chemical contamination.

The ten particle characteristics described below should be important to tribology analysts and lubrication professionals. Each of these characteristics or traits can influence the health and performance of hydraulic machinery. While the name of the trait may be familiar to many people, the damage it causes may be less so.

Particle size. Particle size is usually defined as a particle's equivalent spherical diameter in microns (micrometers). This relates to the diameter of a sphere as having the equivalent two-dimensional projected area as an irregular-shaped particle in question. Automatic particle counters size particles on this principle, using the projected blockage of light from particles.

Particle size is important because it characterizes the particle's ability to bridge the working clearances of moving machine surfaces. When large particles get crushed into smaller particles, they tend to get closer in size to a machine's working clearances. The closer the particle size is to these working clearances, the more readily it can enter the gap and cause abrasion or surface fatigue to opposing surfaces. For instance, a single 40-μm particle can theoretically be broken into 512 individually-destructive 5-μm particles. Hence, restricting the ingression of this 40-μm particle, or removing it before crushing can occur, should be a maintenance priority [3].

Surface area. When large particles break into many smaller particles, the cumulative surface area in contact with the oil increases many fold. For instance, if you break a particle into 100 equal-size pieces, you have roughly 4.5 times more interfacial surface area. So, in the previous example, a 40-μm particle, when broken down into 5-μm particles, will produce eight times more surface area in contact with the oil. The more surface area relative to particle mass, the slower the particle settles (longer residence time in the oil), the more it attracts and emulsifies water, the more it can incite catalytic chemical reactions with the oil, the more it can tie up the performance of polar additives (like antiwear agents, rust inhibitors and the like), and the more air bubbles it can nucleate, thus inhibiting their efficient detrainment from the oil.

Particle shape/angularity. Particle shape/angularity is a central risk-factor relating to the wear and damage caused by particles. Spherical-shaped particles are like ball bearings: They may cause surface indentations but are much less likely to cut or abrade. On the other hand, particles with high annularity (possess sharp, acute angles between facets) are more prone to impart three-body abrasion, leading to material removal. This is characterized by the study done by Hamblin and Stachowiak as shown in Figure 5.2 [4].

Angular particles are generally caused by the crushing (comminution) of large particles into smaller particles (Figure 5.3). If a spherical particle were broken into 100 smaller particles having the general shape of cubes, this would expose sliding machine surfaces to 800 angular edges.

Hardness. Hardness relates to a particle's compressive strength, that is, its resistance to deformation (plastically or elastically) or fragmentation by crushing. Particle hardness relative to surface hardness largely defines its ability to cause wear and fatigue. As a point of reference, common dirt consists largely of silica and alumina particles, which are harder than all metallic surfaces used in hydraulic components. Only ceramic surfaces found in some bearings would be harder. The relative hardness of common particles is shown in Table 5.1.

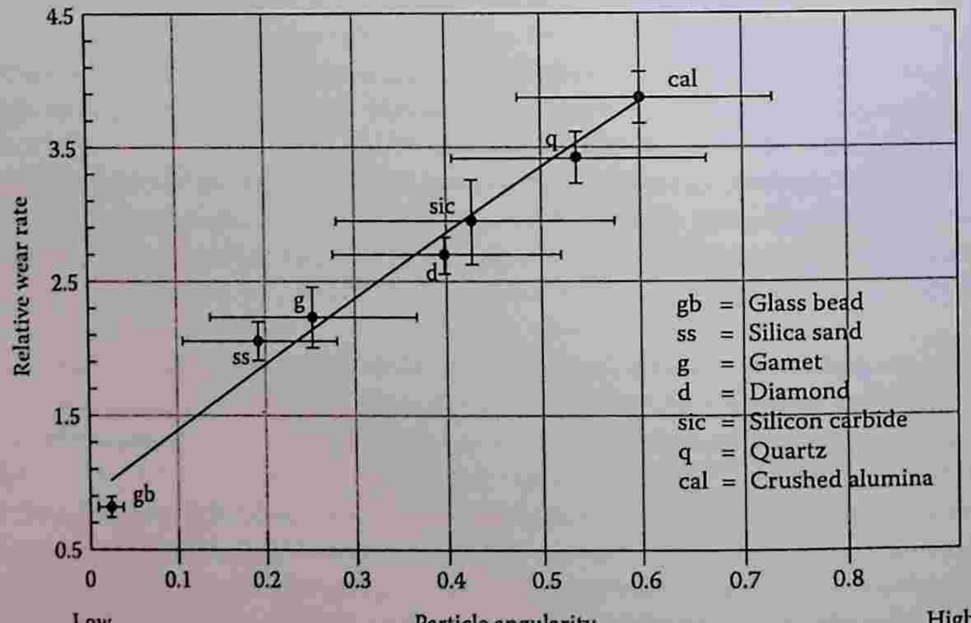


FIGURE 5.2 Wear rate versus particle angularity.

FIGURE 5.3 Angular rock dust from mining, quarry or excavation.

Density. Density, or specific gravity, influences how buoyant particles are in lubricating oils. Heavy particles will settle more rapidly in tanks and sumps. The densities of common particles are shown in Table 5.1 above. It takes only 2.8 minutes for a 20-μm babbitt particle to settle one-half inch in an ISO 22 hydraulic fluid, based on the principles of Stokes Law. Heavy particles are also more prone to cause particle impingement erosion, as oil circulates at high velocity, sending heavy and hard particles on destructive trajectories [1].

Composition. While terrain dust is known for its wear-inducing potential due to its hardness, it is also rather chemically inert. However, the wear particles generated by this dust (plowed up by abrasive and surface fatigue) that become suspended are typically not inert. This is due to the fact that these nascent wear particles are often composed of iron, copper, or tin. Although less hard and abrasive, wear metals aggressively promote oil oxidation, which in turn contributes to the formation of corrosive acids, varnish, and sludge.

Polarity. Many particles have unique polar affinities or possess ionic charges. This can lead to the mass transfer and depletion of polar oil additives such as rust inhibitors, antiwear agents, detergents, dispersants and extreme pressure additives, which are more prone to hitch a ride on these particles. Also, polar particles are apt to cluster and obliterate fine oil passages, oil ways, weep holes, and silt lands. This is compounded if water is present, which has a tendency to cling to polar solid contaminants, thus further promoting obliteration and the formation of emulsions and sludge.

Magnetic susceptibility. Permanent magnets are used in some filters and on line wear particle sensors. Particles of iron or steel that are attracted to a magnetic field are preferentially separated from the oil by these devices. Later, any particles that may have sloughed off these separators and sensors (due to shock or surge-flow conditions) are often left magnetized. They can then magnetically grip onto steel orifices, glands, and oil ways restricting flow or simply interfering with part movement. Additionally, directional control and servo-valves commonly used in hydraulic systems deploy the use of electro-magnets in their solenoids. The actuation of these valves can be adversely affected by the magnetic susceptibility of iron and steel particles that are attracted by the solenoid [5].

TABLE 5.1
Examples of Particle Hardness and Density

Particle Type	Typical Specific Gravity	Mohs Hardness*
Burrs and machining swarf	6–9	3–7
Grindings	6–9	3–7
Abrasives	3–6	7–9
Floor dust	1–5	2–8
Road dust (mostly silica)	2–6	2–8
Mill scale	5	NA
Coal dust	1.3–1.5	NA
Ore dust	Various	Various
Wood pulp	0.1–1.3	1.5–3
RR ballast dust (limestone)	2.68–2.8	5–9
Quarry dust (limestone)	2.68–2.8	5–9
Foundry dust	2.65	7
Fibers	Various	Various
Slag particles (blast furnace)	2.65	7
Aluminum oxides	NA	9
Red iron oxides (rust)	2.4–3.6	5–6
Black iron oxides (magnitite)	4–5.2	5–6
Copper oxides	6.4	3.5–4
Tool steel	7–8	6–7
Forged steel	7–8	4–5
Cast iron	6.7–7.9	3–5
Mild steel	7–8	3
Alloys of copper, bronze	7.4–8.9	1–4
Alloys of aluminum	2.5–3	1–3
Babbitt particles	7.5–10.5	1
Soot	1.7–2.0	NA

* Mohs hardness scale 1–10, diamond = 10, fingernail = 1.

Conductivity. There are some positive characteristics of particle contamination. For instance, in recent years the electrification of hydraulic fluids and lubricating oils has become a greater and more common problem due to the high purity of basestocks which are frequently used by formulators. Base oils in the categories of API Groups II to IV present the highest risk.

Circulating oil can build a static charge in the oil due to molecular friction. This can lead to electrical arcing within the body of the oil, charring the oil in its path. Conductive particles are effective at dissipating charges, preventing damage to the oil from static discharge. According to one study, particle contamination equivalent to an ISO 18/15 was sufficient to dissipate static charge buildup in contrast to low contaminant levels of ISO 13/10 or cleaner, which led to strong spark discharges [6].

Particle count. As previously discussed, a single particle of the right size, shape, and hardness is a potentially destructive contact (Figure 5.1). Two such particles proportionally multiply the risk wear rate, and so forth. In fact, the total amount of surface material removed could be four to ten times the weight of the original offending particle. This risk is greatest for unfiltered or poorly-filtered systems. This is due to the reproductive cycle of particle contamination—particles make more particles. With each successive generation of particles there is increasing risk of wear and lubricant degradation. This is because of the cumulative growth of particles, total interfacial surface area, and nascent metal composition (causing catalytic chemical reactions). Controlling particle population growth is a fundamental and effective strategy in stabilizing machine reliability and fluid health.

5.4 PROACTIVE MAINTENANCE AS THE CONTAMINATION CONTROL STRATEGY

While it is not practical to eradicate all contamination from new and in-service hydraulic fluids, control of contaminant levels within acceptable limits is both accomplishable and important. Controlled systems, by definition, are those which include measurement and feedback loops. This explains why instruments called particle counters may be the most widely-used on site oil analysis tools today. Proactive maintenance, employing the use of particle counters, is the central strategy for success in reducing maintenance costs and increasing machine reliability [7].

While the benefits of detecting abnormal machine wear or an aging lubricant condition are important and frequently achieved with oil analysis programs, they should be regarded as being lower on the scale of importance when compared to the more rewarding objective of failure avoidance. This is achieved by treating the causes of failure (proactive maintenance), and not simply the symptoms (predictive maintenance). In fact, proactive maintenance is the only effective way to achieve simple solutions to complex machine maintenance problems. Restated, it is far easier to prevent a failure through root cause control than to troubleshoot an incipient or impending failure control that is already occurring [8].

Whenever a proactive maintenance strategy is applied, three steps are necessary to ensure that its benefits are achieved (Figure 5.4). Since proactive maintenance, by definition, involves the continuous monitoring and controlling of machine failure root causes, the first step is simply to set a target, or standard, associated with each root cause. In oil analysis, the root causes of greatest importance relate to fluid contamination (particles, moisture, heat, coolant, etc.). This target should be sufficiently rigorous as to reduce wear and increased reliability.

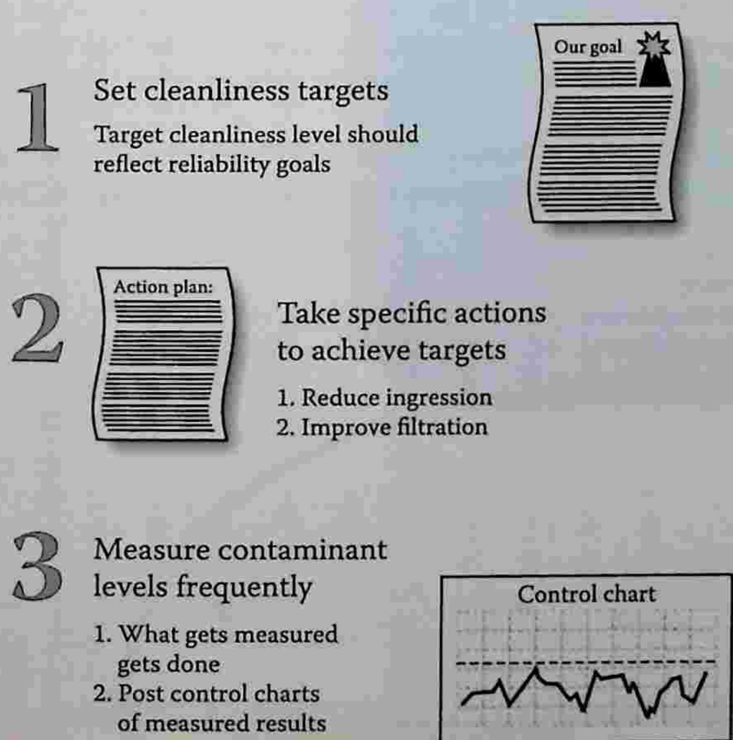


FIGURE 5.4 Three steps to implementation of proactive maintenance.

However, the process of defining precise and challenging targets (e.g., high particle cleanliness) is only the first step (discussed in the following section). Control of the fluid's conditions within these targets must then be achieved and sustained. This is the second step and often includes an audit of how fluids become contaminated and then systematically eliminating these entry points. Often, better filtration and the use of separators may also be required.

The third step is the vital action element of providing feedback to the oil analysis program. When exceptions occur (e.g., over-target results) remedial actions can then be immediately commissioned. Using the proactive maintenance strategy, contamination control becomes a disciplined activity of monitoring and controlling fluid cleanliness, not a reactive activity of responding to high dirt and wear debris levels.

The relationship between proactive and predictive maintenance is perhaps best illustrated in the graph shown in Figure 5.5 below. The Proactive Domain is influenced by the control of root causes such as particle contamination, with the goal of extending this domain indefinitely, if possible. The Predictive Domain starts at failure inception, which is also the end of the Proactive Domain. Its goal is early detection, while there is still considerable Remaining Useful Life (RUL) of the system components. The closer the point of failure detection is to the point of failure inception, the more effective the maintenance response will be.

If an impending failure goes undetected, then catastrophic failure is imminent. During this failure (Protective Domain) the objective is to minimize the failure severity (repair costs) and to prevent collateral damage to other system components. When the life extension benefits of proactive maintenance are flanked by the early warning benefits of predictive maintenance, a comprehensive condition-based maintenance program can result [9].

5.5 SETTING RELIABILITY-BASED CLEANLINESS TARGETS

While there are numerous methods used to arrive at target cleanliness levels for fluids and lubricants in different applications, most consider both the importance of machine reliability and the general contaminant sensitivity of the machine or system. This approach enables customization of the target to: (a) the reliability goals of the machine owner, (b) the risk of contamination from the operating environment, and (c) the contaminant tolerance of the hydraulic system. A common example of this approach is shown in Table 5.2 and is referred to as the Target Cleanliness Grid (TCG) [10].

The TCG utilizes the Reliability Penalty Factor (RPF) and the Contaminant Severity Factor (CSF), which are arrived at through a subjective scoring system (see Figures 5.6 and 5.7). The RPF

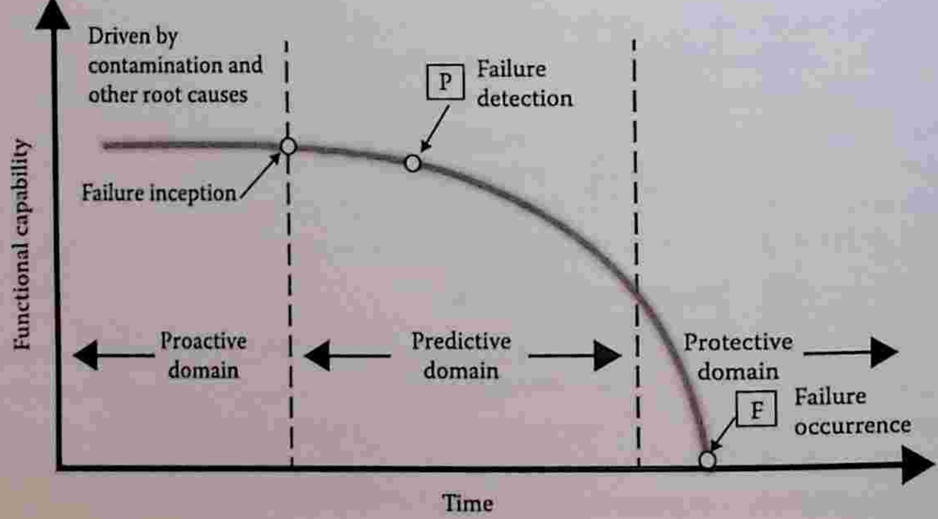


FIGURE 5.5 Condition-monitoring domains in the PF interval curve.

TABLE 5.2
Target Cleanliness Grid (TCG) for Setting Cleanliness Targets

Reliability Penalty Factor (RPF) Cost, Safety, and Business Interruption Penalty from Failure										
10	19/16/13	18/15/12	17/14/12	16/13/11	15/12/10	14/11/19	13/10/8	12/10/8	11/9/7	10/9/7
9	19/16/13	19/16/13	18/15/12	17/14/11	16/13/10	15/12/10	14/11/9	13/10/8	12/9/7	11/9/7
8	20/17/14	20/17/13	19/16/13	18/15/12	16/13/11	15/12/10	14/11/9	13/10/8	12/9/8	12/9/7
7	21/17/14	20/17/14	19/16/13	18/15/12	17/14/11	16/13/10	15/11/9	14/11/9	13/10/8	12/10/8
6	21/18/15	21/18/14	19/16/13	18/15/12	17/14/11	16/13/10	15/12/9	14/11/9	13/10/8	12/10/8
5	22/18/15	21/18/15	20/17/14	19/16/13	18/15/12	17/14/11	16/14/11	15/13/11	14/11/10	13/11/9
4	22/19/16	22/19/16	20/17/14	19/17/14	18/15/13	17/14/11	16/14/11	15/13/10	14/12/9	13/11/9
3	22/19/16	22/19/16	21/18/15	20/17/14	19/16/13	18/15/12	17/14/11	16/14/11	15/13/10	14/12/9
2	23/20/17	23/20/17	22/19/16	21/18/15	20/17/14	19/16/13	18/15/12	17/14/11	16/14/11	15/13/10
1	24/20/17	23/20/17	22/19/16	21/18/15	20/17/14	19/16/13	19/16/12	18/15/11	17/14/11	16/14/11
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Contaminants Severity Factor (CSF)
Sensitivity of Machine to Contaminant Failure

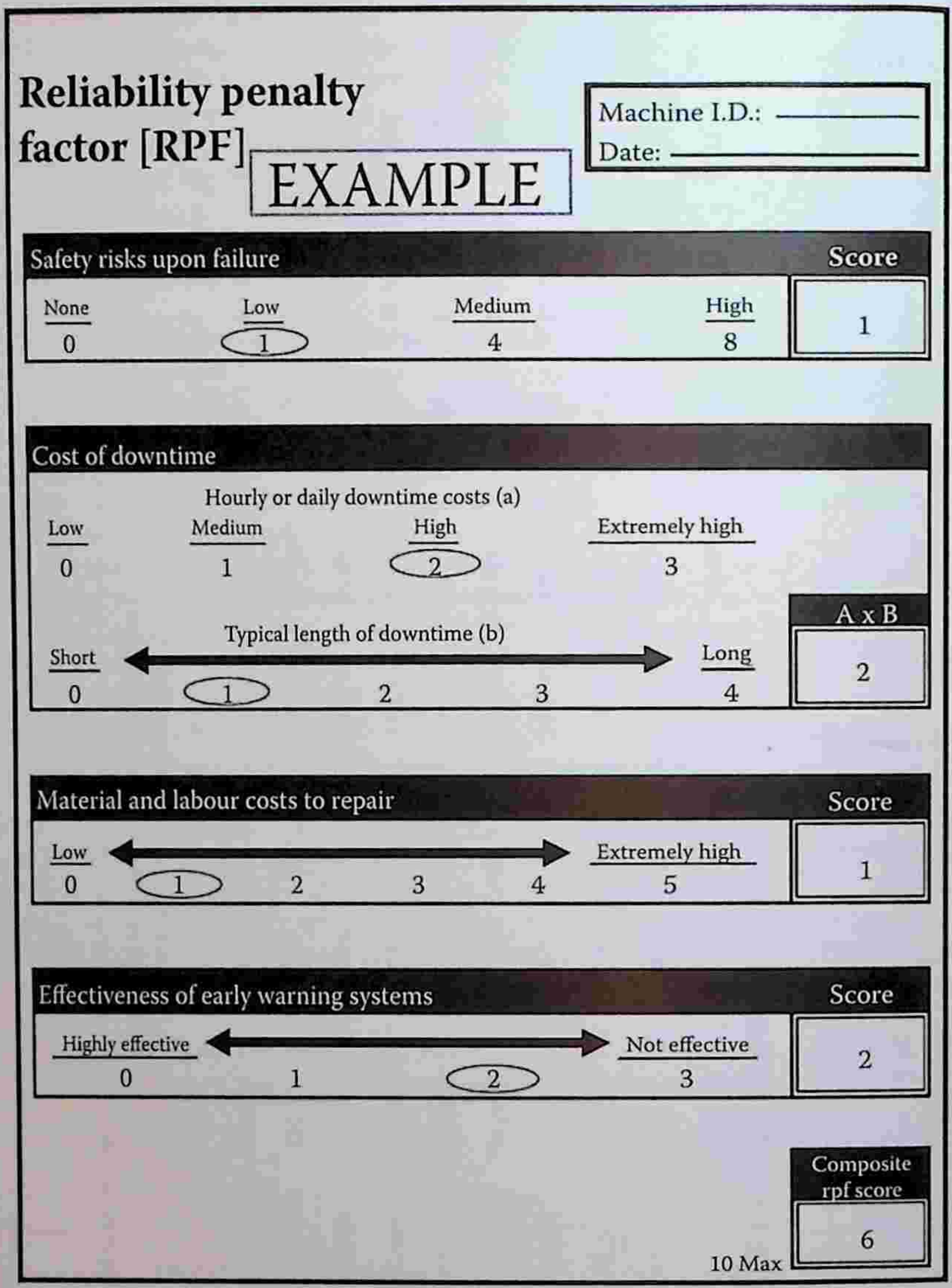


FIGURE 5.6 Reliability Penalty Factor (RPF).

scores system reliability needs based on repair cost, safety, and business interruption risks. For instance, the score for flight control hydraulics on commercial aircraft would be markedly different to that for agricultural hydraulics. The CSF scores the sensitivity of the system and its components to particle contamination and the likelihood of contaminant ingression from the work environment. High-pressure hydraulics with servo-valves operating in a mining environment would score much differently than a low-pressure punch-press in an automotive plant. The RPF and CSF combine on the TCG to select a target cleanliness utilizing the ISO Solid Contaminant Code (ISO 4406:99) [10,11] (see Figure 5.8).

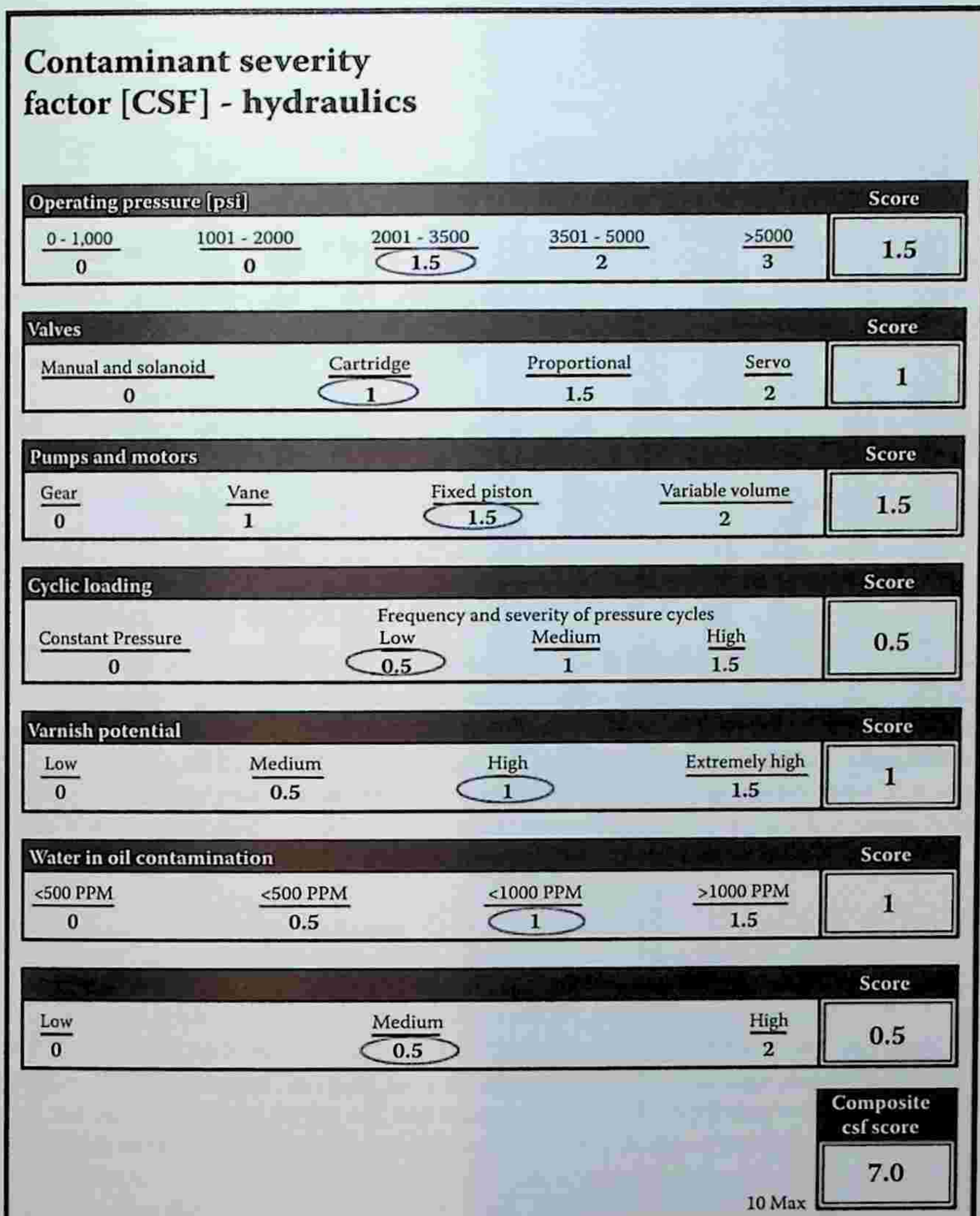


FIGURE 5.7 Contaminant Severity Factor (CSF)—hydraulics.

Target cleanliness can also be viewed in terms of filtration and contaminant exclusion as seen in the conceptual Contamination Control Balance [1] of Figure 5.9. Starting at the left scale, the desired machine service life is defined (say in thousands of hours). With the balance pointed to this reliability goal, the corresponding target cleanliness is defined on the vertical scale to the right. Maintaining the balance at that angle requires adjustments to the ingression rate, filter flow rate, and filter capture efficiency. From the balance, we can see that the reliability objective defines the target cleanliness which, in turn, defines the ingression and filtration needs of the system.

What does not work is using universal cleanliness targets for all machinery. Precision maintenance is about customized choices, not generalized default choices. Once these precision targets are

Example particle count	
Size (microns)	Count larger than size per ml
4	1752
6	517
10	144
14	55
20	25
50	1.3
75	0.27
100	0.08

ISO 4406:99
$R_4/R_6/R1_4$

1752 particles > 4 µm/ml

517 particles > 6 µm/ml

55 particles > 14 µm/ml

ISO 18/16/13

Number of particles per ml		
More than	Up to and including	Range number (r)
80,000	160,000	24
40,000	80,000	23
20,000	40,000	22
10,000	20,000	21
5,000	10,000	20
2,500	5,000	19
1,300	2,500	18
640	1,300	17
320	640	16
160	320	15
80	160	14
40	80	13
20	40	12
10	20	11
5	10	10
2.5	5	9
1.3	2.5	8
0.64	1.3	7
0.32	0.64	6
0.16	0.32	5
0.08	0.16	4
0.04	0.08	3
0.02	0.04	2
0.01	0.02	1

FIGURE 5.8 Under ISO 4406:99, a sample is given a fluidcleanliness rating using the above table. To do this, thenumber of particles greater than three size ranges, 4, 6 and 14 µm are determined in the equivalent of onemilliliter of sample. In the above example, the particlecount distribution shown in the table on the leftcount distribution shown in the table on the lefttranslates to an ISO 4406:99 rating of 18/16/13.

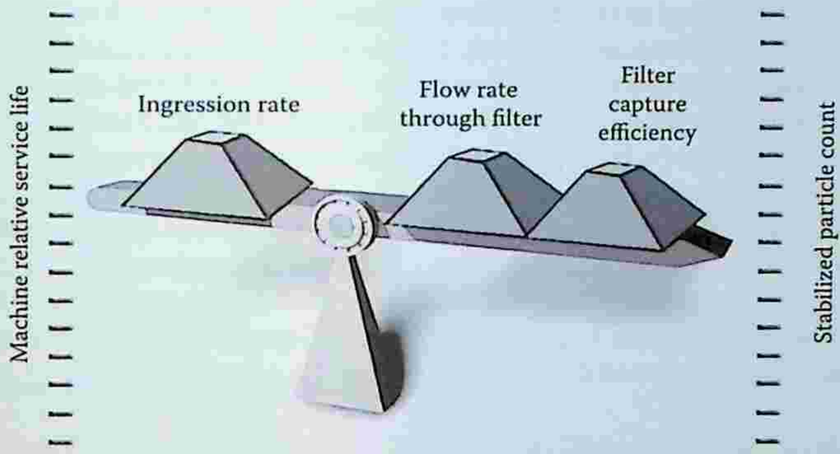


FIGURE 5.9 Contamination control balance.

set they should be communicated to the maintenance staff and each system or machine should be labeled, with the targets made conspicuously visible.

5.6 CONTAMINANT INGRESSION AND EXCLUSION

For many machines, the exclusion of contamination is the only practical way to control contamination. This is because these machines either have no filter or the filter in use is coarse, providing no real protection in the particle size range of critical oil films and surfaces. When particles are not removed by filtration or by settling, a lubricant's contaminant level equals the machine's service hours multiplied by the number of particles ingressed per hour (ingression rate). For machines exposed to high ambient dust, particle counts can exceed target levels in just a few hours. After days of exposure, a fluid can turn into more of a honing compound than a lubricating medium.

5.6.1 Ingression and Mass Balance

Even hydraulic systems with good filters are often faced with ingression challenges. To maintain contaminant levels within targets, the filter must remove particles at a rate equal to the ingression rate (mass balance). The lower the target cleanliness level (higher cleanliness), the more difficult this becomes. This is because, in order for a fluid to stay within these high cleanliness targets, particles are not densely packed in the oil, but rather are sparsely distributed—few and far between. This means that for every gallon of fluid that enters the filter, there are few particles from that gallon that are available to be removed. Yet the filter must still remove particles at a rate equal to the ingression rate, otherwise the contaminant level will rise. This places increasing demand on the quality and capture efficiency of the filter (percent particles removed above a certain size).

Also sharply influencing this is the flow rate of the oil entering the filter. The flow provides the necessary conveyance of particles to the filter. If flow rates are low, filters with even 100% capture efficiency (Beta ratio equal to infinity) cannot remove enough particles to keep pace with ingression, causing contaminant levels to exceed targets. The higher the target cleanliness (dirty oil), the higher the minimum required flow rate for a given filter.

5.6.2 Cost of Excluding Dirt

It is often said that the cost of excluding a gram of dirt is only about 10% of what it will cost you once you let it enter the oil. Dirt puts stress on additives, the base oil, and machine surfaces. Also, the cost to filter a gram of dirt from the oil is much higher than the cost of filtering a gram of dirt from the air intake/breather.

The word "ingression" refers to the introduction of particles into lubricants and hydraulic fluids, regardless of the source (external and internal). Figure 5.10 organizes common ingression sources into three subcategories: (1) built-in, (2) ingested, and (3) generated. Depending on the nature of the machine, the ingression rate and sources can vary considerably. For clean-environment indoor equipment, the primary sources can be from process fluids and internal generation (wear, corrosion, etc.).

Hydraulic systems that operate in outdoor work environments can encounter high levels of ambient dust, representing as much as 95% of all particles that enter the oil. Machines that operate close to the ground are prone to higher ingression rates than those that operate high in the air (including aviation) or away from the ground altogether (marine). For outdoor machinery, climate conditions have a marked influence on particle ingestion. For instance, rain and damp soil keep particles from becoming airborne. High winds and dry climates do just the opposite.

5.6.3 Controlling Top-End Ingression

For many machines, reducing ingression means reducing top-end ingression—that is, the particles entering through fill ports, vents, breathers, hatches, inspection ports, and other headspace openings. There are numerous ways to control top-end ingression, such as:

- **Purge methods.** This involves the introduction of a clean gas or aerosol into the headspace of the reservoir. A slight positive pressure is maintained to prevent the entry of ambient air. Examples include instrument air purge, oil mist purge, and nitrogen purge.
- **Isolation methods.** Expansion chambers, piston/cylinder reservoirs and bladders have been used to isolate headspace air from ambient air in order to prevent contamination. One disadvantage is that moisture (humid air) is often unable to escape from the headspace. This also locks moisture into the oil as well. In some cases, users have reported that this has led to heavy corrosion.

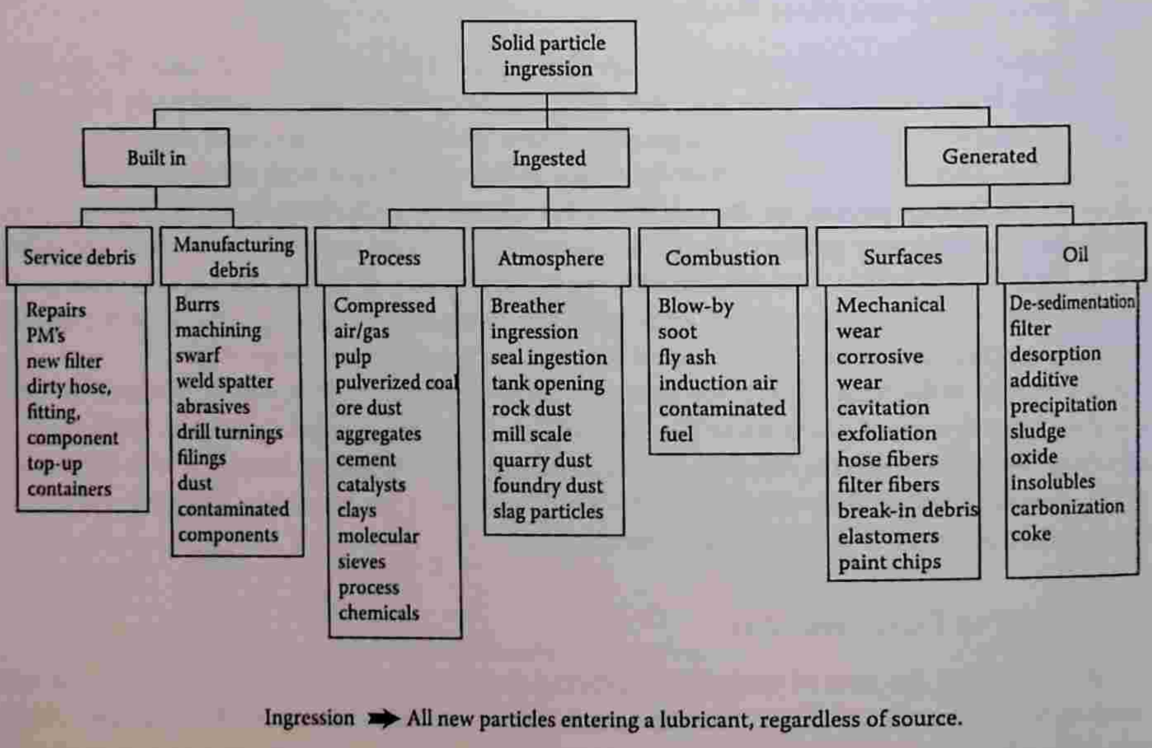


FIGURE 5.10 Categories of particle ingression.

- **Filter breathers.** If reservoirs and sumps can be sealed tightly, such that all air exchanged between the atmosphere and the headspace can be directed through a single port, then high-quality filter breathers can be used to remove dust from incoming air at that port (vent). The quality of the filter (capture efficiency) should be no less than that of the oil filter in use.

Figure 5.11 presents a table of the headspace management options for both particulate and moisture ingression risks. The ingression control strategy needs to correspond to the machine design, operating conditions, and exposures [12].

5.6.4 Map Contaminant Ingression Sources

The first step of a contamination control program is to identify a machine's target cleanliness level as previously mentioned. Next, identify the source and entry points of particles. This generally involves conducting a contaminant ingression study.

Because particles are often internally generated, a contaminant ingression study is not simply a matter of doing a walk-down inspection to look for top-end ingression points. For many machines there is a need to examine particles found in used filters, bottom sediment, oil drains, and live zone oil samples as a means to determine their origin. This can be done using microscopic methods and by element analysis (testing particles for copper, lead, iron, silicon, etc.). Multiple oil sampling points in circulating equipment can help to isolate ingression to certain components like hydraulic cylinders. Additionally, taking particle counts up and downstream of filters while the machine is in normal service can be helpful in identifying the approximate ingression rate (number of particles entering per unit time).

Figure 5.12 shows how this information can be used to map the contaminant sources for a hydraulic system. In the hypothetical example, the figure shows particle and moisture entry relative to six contributing sources. Furthermore, the headspace and ventilation contributing source shows a breakout of six sub-entry points for these contaminants. This same detailed breakout could be charted for the other main contributing sources. Once these sources are understood, plans should be developed and deployed to systematically restrict ingression, starting at the highest ingression points [12].

	Controls these contaminants or these sources of contaminants entering headspace				Other factors	
	Environmental dust	Humidity or steam	Rain or washdown sprays	Ingression past open hatches, inspection ports, etc	Initial costs	Maintenance costs
Spin-on filter or enclosed cartridge filter used as a breather	Y	N	N	N	L	M
Desiccant filter breather	Y	Y	N	N	L	M
Dry instrument air or nitrogen purge	Y	Y	Y	Y	M	M
Oil mist purge	Y	Y	Y	Y	M to H	M
Desiccant headspace dryer	N	Y	M	N	M	M
Mechanical dehumidifier system	N	Y	M	N	H	L
Expansion chambers, bladder, etc.	Y	Y	Y	N	H	L

Y = Yes N = No M = Marginal L = Low H = High

FIGURE 5.11 Headspace management options for both particulate and moisture Ingression.

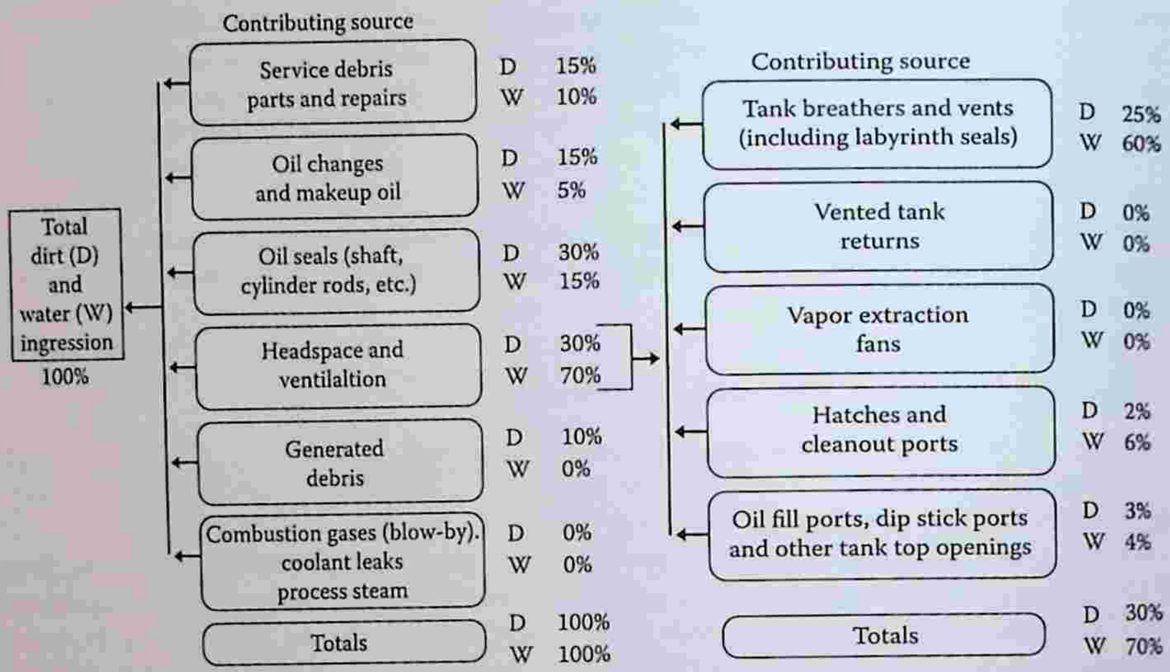


FIGURE 5.12 Sample contaminant ingression mapping chart.

5.6.5 Roll-off Cleanliness

Roll-off cleanliness is the level of cleanliness expected to be achieved when assembling any component or system with clean parts in a controlled manufacturing environment. The purpose of maintaining a high level of roll-off cleanliness is to minimize the overall original system contamination and reduce the premature damage caused to various system components upon startup.

Built-in contamination is the inadvertent contamination left in a system or component during initial assembly or system rebuild. The quality and cleanliness of the manufacturing environment is paramount to limiting the amount of built-in contamination. Therefore, the important role of cleanliness begins with the control of contamination in manufacturing environments and the associated work and assembly practices. Much like the in-service control of hydraulic fluid contamination, the work zones of a manufacturing facility should also be viewed as “controlled areas.” Some of the areas that must be controlled include:

- Assembly, rebuild, cleaning and repair areas;
- Component, parts and fluid storage areas;
- Shipping and receiving, purchasing and the supplier areas.

Two standards relating to roll-off cleanliness for hydraulic systems are the following:

- ISO/TR 10949 – Hydraulic fluid power – Component cleanliness – Guidelines for achieving and controlling cleanliness of components from manufacture to installation.
- ISO/TS 16431 – Hydraulic fluid power – Assembled systems – methods for achieving roll-off cleanliness.

5.7 FILTRATION AND REMOVAL OF PARTICLE CONTAMINATION

Referring back to the contamination control balance (Figure 5.9), after all efforts have been expended to reduce ingression, the only remaining areas of focus are in the decisions related to the quality, performance, and economy of filtration. There is a price tag for removing dirt from oil. For large plants and fleets operating in dusty environments, the cost can be substantial—hundreds of thousands of dollars per year. With that said, where quality filtration is needed to achieve cleanliness targets, there are still several options to get the most cleanliness for the fewest filtration dollars, referred to as "filter economy."

5.7.1 Select Filterable Hydraulic Fluid

Consider testing fluid filterability, especially for filters with mean pore sizes of 5 μm or below. Even if new fluids are relatively clean, they may be simply non-filterable (or poorly filterable). Many hydraulic fluids exhibit unique differences when it comes to filterability. Refer to the standard ISO 13357 for filterability testing for both wet and dry conditions [12].

There are several contributing factors that cause impaired fluid filterability. For instance, many new lubricants may have soft, organic impurities or metal soaps that contribute to premature filter plugging. Some of this filterable material may be undissolved additives or perhaps stringy polymeric additives (e.g., VI improvers or pour point depressants) which partially restrict flow through fine pore-size filter media.

Another cause of poor filterability relates to old oils that suspend a high population of very small particles. Often these particles fall below the size detection limit of optical particle counters. While these particulates may be smaller than the mean pore of the filter media (say less than 2 μm), through a mechanism known as secondary and tertiary flow restriction, the filter can become rapidly plugged by these particles. In such cases, an oil change may be a more economical solution than filtration.

Undissolved moisture (above the oil's saturation point) can also shorten a filter's life. Water has a tendency to absorb into the pores of cellulose media or adsorb onto filter media fibers. In either case, the presence of water can shorten filter life and can even impair the structural integrity of the filter media. Water also contributes to oxidation and hydrolysis of the oil, which can produce gums and resins, leading to premature filter plugging.

5.7.2 Seek Economic Filter and Filtration Choices

The process of making economic filtration choices can be broken down into two categories: economic filters and economic filtration, which are similar concepts although with certain differences. Economic filters relate to such considerations as filter size, media type, dirt-holding capacity, and so forth. Economic filtration relates to the system and operating conditions such as flow density, pressure, filter location, use of multiple filters, use of centrifuges, and so on.

The following is a list of factors and conditions that, with some exceptions, can improve filter and/or filtration economy [13].

1. **Low filter pressure.** Spin-on filters and even disposable cartridge filters that are designed for high-pressure systems generally cost more for the same dirt-holding capacity than most low-pressure filters.
2. **Low-collapse filters.** High-collapse hydraulic filters generally do not have bypass valves. These filter elements are robustly constructed to resist desorption, media migration, and collapse. These often unneeded attributes are more expensive than common low-collapse filters.
3. **Oversized filters.** The lower the oil's flow rate relative to the maximum allowable element flow rate (catalog flow rate), the better the filter economy (see Figure 5.13). This is also referred to as "flow density." For instance, doubling the size of a filter may triple the dirt-holding capacity (and triple the filter's service life) but may cost less than twice the price (per filter element). Additionally, low-filter flow density also reduces energy consumption costs [14].
4. **High dirt-holding capacity elements.** The technologies used in filter media and filter element construction vary considerably. For instance, mean fiber diameter, fiber composition, pore density, pore depth, tapered pore structure and cladded media are design factors that

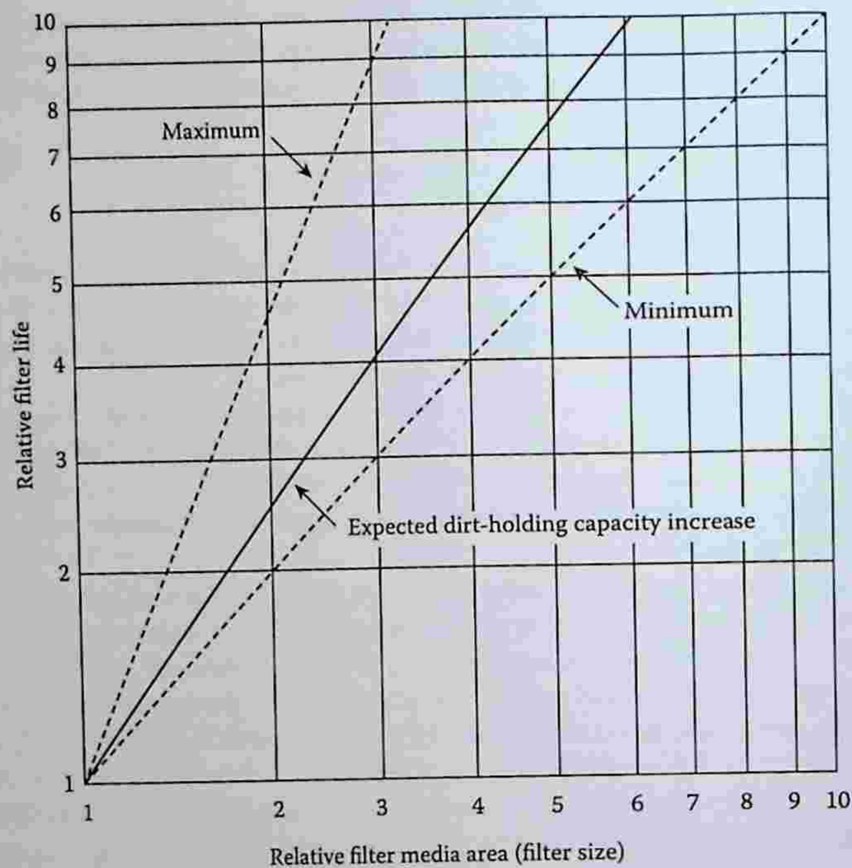


FIGURE 5.13 Filter size effect (media area) on dirt-holding capacity.

influence the dirt-holding capacity of a filter. There are also differences in pleat geometry, flow direction and element construction that influence the total media area per filter element unit volume, which in turn influences oil flow density. The element construction also influences the risk of pleat movement, flow channeling, fatigue and structural integrity. As mentioned above, the lower the effective flow density (flow rate per unit media area), the higher the dirt-holding capacity and the longer the filter's service life. Most hydraulic filters are tested to ISO 16889, which reports information on dirt-holding capacity and capture efficiency (Beta ratio).

5. **Series filtration.** Two or three filters arranged in series have been found, in certain cases, to improve filtration economy. The oil passes through coarse, lower-cost filters before reaching the final polishing filter. Most of the dirt is removed by these lower-cost filters first, allowing the more expensive polishing filter to have extended service life.
6. **Warm oil filtration.** Configuring filters upstream of heat exchangers can extend service life as well. The lower viscosity of the warm oil enables the oil to flow with less restriction through the filter media, delaying the time it takes to reach the terminal pressure drop (filter change alarm). As mentioned, warm oil also improves fluid filterability. However, exceedingly high oil temperatures present many other challenges such as premature oil oxidation and thermal fatigue of the filter media.

5.7.3 Key Filter Selection and Location Considerations

Selecting and locating hydraulic filters to meet cleanliness and reliability objectives is an engineering process and the details of which are beyond the scope of this chapter. However, an overview

TABLE 5.3
Filter Selection Decision Table

Filter Selection Decision	Why It Matters	Inputs Needed to Make the Decision
Beta (time-weighted average)	Defines the life cycle particle capture efficiency at certain particle sizes. Helps to determine what target cleanliness can be achieved.	Target cleanliness level.
Beta (life cycle minimum)	Defines worst-case capture efficiency. Helps define reliability risk in protecting system.	Contaminant sensitivity of high-risk components, for example, servo valves.
Duty cycle tolerance (surge flow, flow cycling, vibration, shock, etc.)	Some machines produce high duty cycle and therefore are at a high risk of losing filtration performance.	Machine design and application information. Other related factors are pressure/flow cycles (frequency and amplitude), temperature extremes, etc.
Dirt-holding capacity	The dirt-holding capacity helps define the service interval (how often filter must get changed) and the average cost to remove a gram of dirt (filter economy).	Ingression rate, maximum permissible size of the filter, importance of filter economy (budget constraints, etc.).
Filter media type	Some filter media types are incompatible with the expected service life of the filter, temperature extremes, fluid chemistry, duty cycle and pressure differential.	Information on the fluid, duty cycle, required service interval, temperature extremes, and minimum required collapse pressure.
Housing and element size, metallurgy, surface coatings/treatments, maximum allowable operating pressure, ports, canister configuration, mounting brackets/configuration, collapse strength, etc.	Determines whether a filter selection will satisfy filter selection objectives.	Filter location, flow rate at that location, maximum new element differential pressure, maximum required terminal differential pressure, duty cycle, pipe/hose connectors/size/threads, viscosity, fluid type, coldest startup temperature, normal operating temperature.
Need for drainback blocking valves. Need for duplex filtration with switching valve (change-over value)	Relates to whether the filter can be changed on the run and with minimal fluid loss.	Machine operating conditions, frequency of downtime, risk of fluid loss during filter changeouts, etc.
Bypass valve type and setting	Determines what differential pressure permits oil to bypass to avoid starvation, yet risking downstream contamination. Aids in determining the lowest cold-start temperature.	Information on temperature extremes, reliability/safety risks of lubricant starvation, downstream contaminant sensitivity, availability of other filters (serial or parallel).
Filter change indicator and type	Determines the criteria for changing the filter and how the need will be communicated to maintenance staff.	Reliability/safety risks of lubricant starvation, downstream contaminant sensitivity, availability of other filters (serial or parallel), and availability of maintenance staff.

table of the decision steps needed to select filters for hydraulic systems is shown in Table 5.3. Most filter suppliers can provide the engineering support to facilitate the design and selection process. However, it needs to be emphasized that good filter selection at the outset can save considerable costs down the road in terms of filter replacement and machine reliability [11].

There are three primary options for locating a filter on a conventional hydraulic system: (1) pressure-line, (2) return-line, and (3) off-line (see Figure 5.14). In rare cases all three locations have been fitted with filters. If just two locations are selected, it could be any duplex combination of the three options. If just one filter location is fitted with a filter it is usually either the pressure-line or the return-line. The following is a discussion of these three locations:

Pressure-line filtration. Filters located on the pressure line receive the full flow and pressure delivered by the pump. As such, both the filter element and the housing must be designed to handle these often extreme operating conditions. Other unique field and duty cycle conditions can put stress on the pressure-line filter as well including vibration, pressure ripple, shock loading, and temperature cycling.

Pressure-line filters are often selected to mitigate the risk of tank contamination from being dispersed into sensitive work-end system components. Additionally, pumps in failure mode are protected from shelling out a debris field into downstream components when pressure-line filters are used. Because these filters are more expensive than return-line and off-line filters the resultant cost per gram of dirt removed is consequently higher. Many designers put slightly coarser filter elements (say 15 μm) in pressure-line filter housings to gain their protective attributes but rely on other finer filters (say 3 μm) elsewhere for dirt removal.

Return-line filtration. Like pressure-line filters, return-line filters are subjected to extreme operating conditions. However, these conditions have unique differences. Instead of high pump pressure

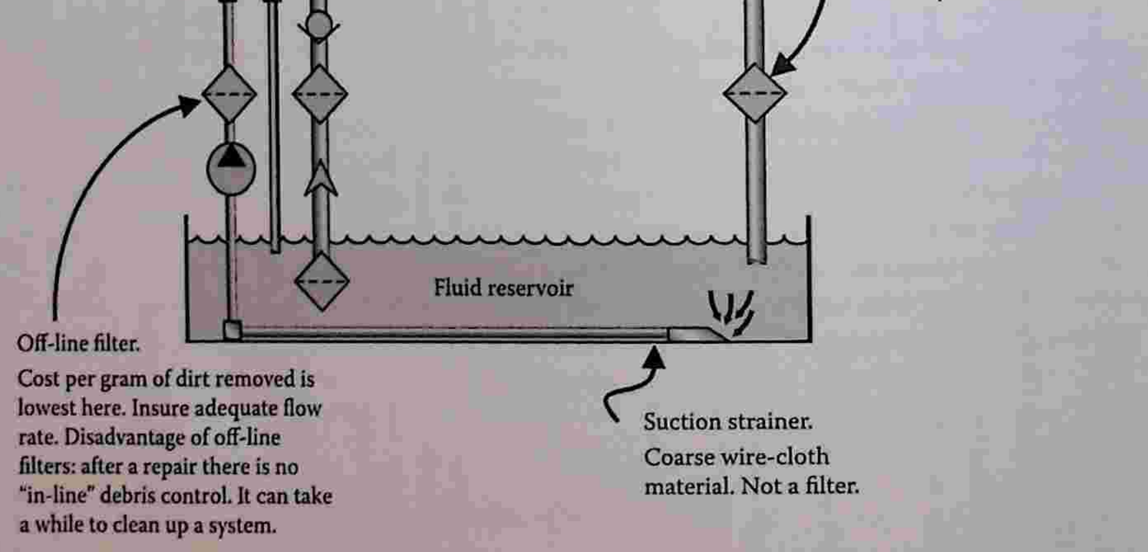


FIGURE 5.14 Filter location options.

and flow, return-line filters generally see only mild line pressures but widely varying flows. The flow rate on the return-line is often not defined by the system pump but rather the load conditions from actuators. Large hydraulic cylinders can induce flow surges that often exceed maximum pump volume by a factor of three or more. Surge-flow conditions can wreak havoc on return-line filter elements causing structural fatigue and impaired capture-efficiency.

Filters specifically designed to resist surge-flow stresses are sometimes specified. In other cases the solution may simply be the use of oversized filters. The benefit of return-line filters is their downstream proximity to the largest particle ingression sites on most hydraulic systems (cylinder rods ingression past wiper seals). Using return-line filters, these particles can be stripped from the oil before reaching the reservoir. Once particles reach the reservoir they present a high risk to the pump since, for a number of reasons, suction-line filters are not a practical reality.

Off-line filtration. Off-line filters are a relatively modern alternative or addition to conventional full-flow filters. These filters sit off the main operating system as a side-loop from the reservoir. A necessary supplemental component to the off-line filter is a pump and motor. Because it does not depend on the hydraulic system, this can run independently, even when the main system is off. The following are some of the additional benefits and attributes of the off-line filtration option:

- Higher initial cost (pump, motor, valves, piping);
- Constant flow optimizes dirt-holding capacity and capture efficiency for a given type of filter;
- Easy to service on the run (filter changes, repairs, etc.);
- Heat exchanges can be built in the loop;
- Sample ports can be installed for sampling on the run;
- Lowest cost to remove a gram of dirt (expensive pressure-line and surge-resistant filters are required);
- Can double for an oil transfer system for adding makeup oil.

5.7.4 Filter Performance Testing and Ratings

Gone are the days when filter manufacturers described the performance of their filters in terms of nominal and absolute micron ratings. Modern hydraulic filters by reputable manufacturers have been tested to assess performance attributes across a range of criteria. These include collapse strength, burst pressures, and structural integrity. However, the contaminant removal characteristics of a filter come from testing that is done in accordance with ISO 16889 (formerly ISO 4572).

Information from this standard includes pressure versus flow characteristics, dirt-holding capacity and filtration ratio (also known as the "Beta ratio"). The filtration ratio is a measure of the particle capture performance of a filter at standardized test conditions (maximum rated flow, constant flow, constant temperature, constant contaminant injection rate, standardized test dust, and fluid). The simplified schematic of a multipass test stand that runs a filter to ISO 16889 is shown in Figure 5.15. The Beta ratio is calculated as the number of particles above a specific micron size (per unit volume of fluid) upstream of the test filter, divided by the number of particles above that same micron size downstream of the filter (see Figure 5.16). The standard calls for the micron size to be reported for filtration ratios of 2, 20, 75, 100, 200 and 1000.

5.7.5 Optimizing Filter Consumption

Changing a filter too late puts the oil and machine in jeopardy. Changing a filter too soon wastes valuable dirt-holding capacity. It has been reported that in many cases the real cost of a common oil change can exceed 10 times the apparent cost of the oil and associated labor. This multiplier may hold equally true for the cost of a filter change. In addition to the cost of the filter, there are

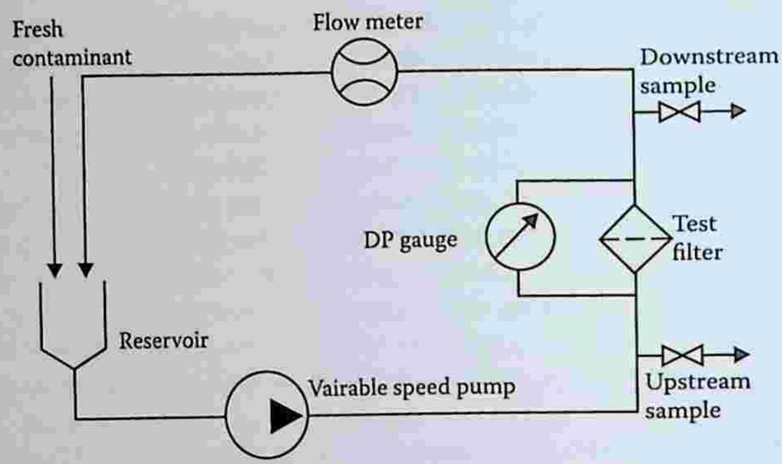


FIGURE 5.15 Multipass filter test stand.

additional costs for labor, inventory, scheduling, used-filter disposal, waste oil disposal, and oil top-off costs (some oil is lost when changing filters) [15].

There are many available technologies to help improve the timing of a filter change. These include pressure-rise profile monitoring, delta-P indicators, bypass indicators, on-line particle counting, and time-out alerts. Multiple methods used together may be the best choice in certain cases. Nonetheless, changing filters "on condition" should be a primary objective towards achieving filter economy.

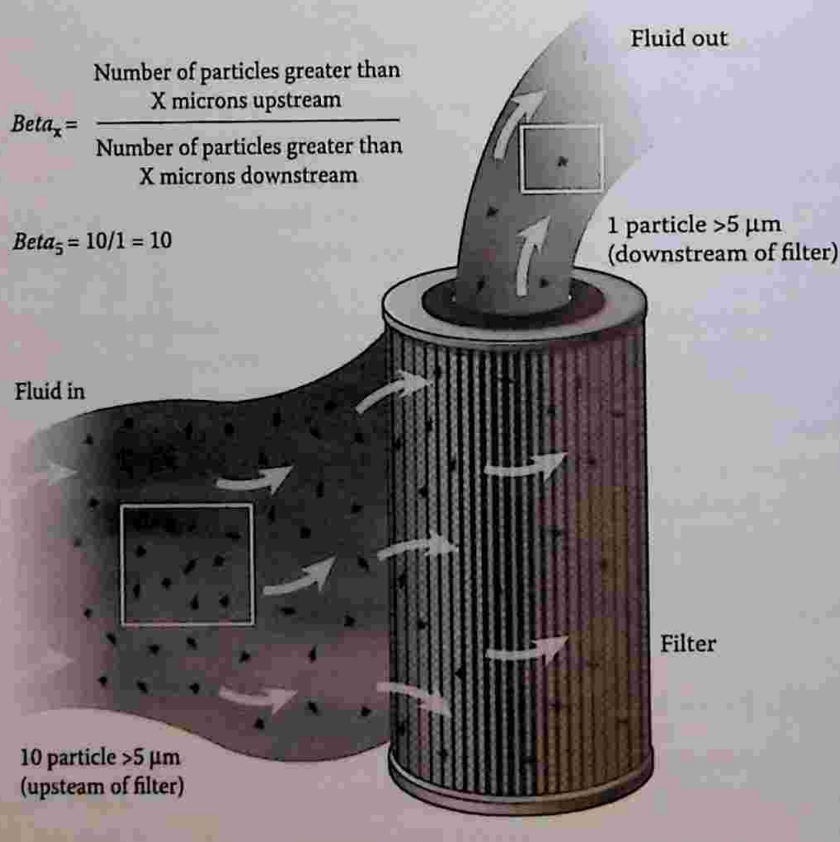


FIGURE 5.16 Filtration ratio (Beta).

5.8 OBTAINING REPRESENTATIVE FLUID SAMPLES FOR CONTAMINANT MONITORING

Oil sampling is one of the most critical factors of successful fluid analysis. Errors in obtaining a representative sample can impair all further analytical efforts, especially particle counting. There are two primary goals in obtaining a representative oil sample. The first is to sample at a location and in a manner that maximizes data density. For instance, the data could be dust particles, moisture, additive levels, or wear debris [10,16–18].

The second goal is to minimize data disturbance. Samples should be extracted in such a way that the concentration of information is uniform, consistent and unaltered by the sampling process. It is important to make sure that the sample does not become contaminated during the sampling. This can distort the data, making it difficult to distinguish what was originally in the oil from what has come into the oil during the sampling process.

To ensure good data density and minimum data disturbance in oil sampling, one should consider the following factors:

- **Sampling location:** Not all locations in a hydraulic machine will produce the same concentration of data. Complex hydraulic systems require multiple sampling locations in order to answer specific questions related to system condition, usually on an exception basis (troubleshooting). Primary sampling points are used for routine sampling and analysis. Secondary sampling ports are used only for troubleshooting to isolate the contaminant-generating/ingressing source.
- **Sampling method:** The procedure by which a sample is drawn is critical to the success of lubricant analysis. Sampling procedures can vary substantially and therefore should be documented and followed uniformly. Technicians should be trained to follow the documented standardized method without variation.
- **Sampling hardware:** The hardware used to extract the sample should not disturb sample quality. It should be easy to use, clean, rugged, and cost-effective.
- **Sample container:** The type and size of bottle and cleanliness help ensure that a representative sample is achieved and fluid volume is sufficient to perform the intended analyses.

It is always advised that one expend the necessary resources for critical systems in order to install proper sampling hardware (valves, access ports, etc.) and ensure that the above goals in oil sampling are achieved. Experience has shown that sampling hardware is not a place to economize; oil analysis is too expensive and unrepresentative samples lead to costly false positives and false negatives.

5.8.1 Strategy for Optimum Selection of Sampling Location(s)

There are several rules for properly locating oil sampling ports on hydraulic systems. These rules cannot always be precisely followed because of various constraints in the machine's design, application, and work environment. However, the rules outlined below should be followed as closely as is reasonably possible [10,16–18]:

- **Turbulence:** The best sampling locations are highly turbulent areas where the oil is not flowing in a straight line but is turning and rolling in the line. Sampling valves located at right angles to the flow path in long straight sections of pipe can result in particle fly-by, especially where there is high fluid velocity and low fluid viscosity. Such conditions can lead to a marked reduction of the particle concentration entering the sample bottle. This can generally be avoided by instead locating sampling valves at elbows and sharp bends in the flow line (Figure 5.17).

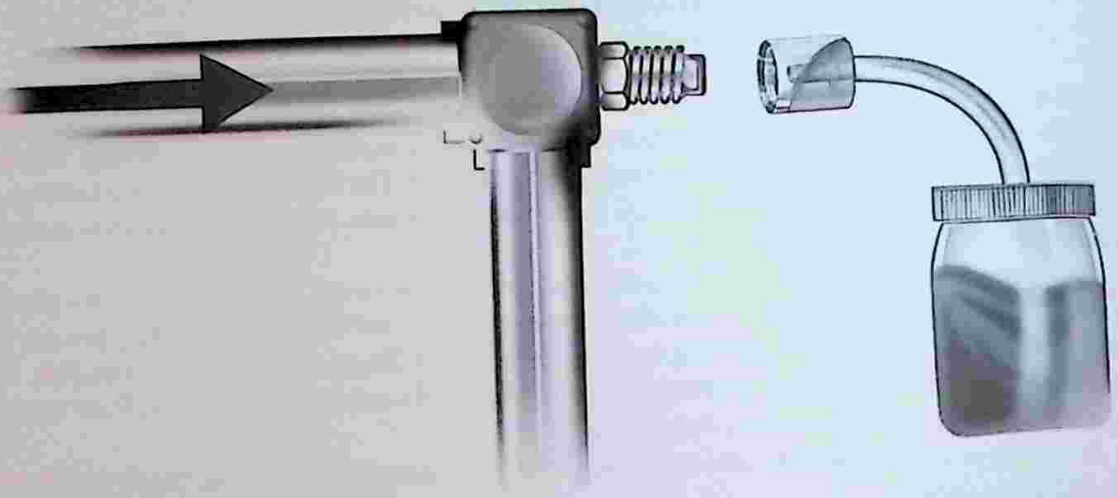


FIGURE 5.17 Sample valve located in a highly turbulent fluid zone.

- **Ingression Points:** Where possible, sampling ports should be located downstream of the components that produce wear particles and potentially ingress particles and moisture. Return-line sample port locations usually offer the most representative levels of wear debris and contaminants in hydraulic systems. Once the fluid reaches the reservoir, wear debris and contamination can become sharply diluted (and potentially undetected).
- **Filtration:** Filters and separators are contaminant removers and, as such, they can remove valuable data from the oil prior to sampling. Sampling valves should be located upstream of filters, separators, dehydrators, and settling tanks unless the performance of the filter is being specifically evaluated.

Just as there are factors that can improve the quality of a sample, there are also other factors which can diminish a sample's quality and should thus be avoided. For example, it is important not to sample from dead pipe legs, hose ends, and stand pipes where the fluid is not moving or circulating. Samples should not be collected after filters or separators, or after an oil change, filter change, or at some time when the fluid would not represent typical conditions. Samples should not be taken when the machine is cold and has not been operating or has been idle. In addition, samples should not be taken from laminar flow zones where a lack of fluid turbulence occurs.

5.8.2 Sampling from Pressurized Lines

When samples need to be taken from pressurized lines the sampling method is often simplified. Figure 5.18 shows four different configurations for sampling from pressurized lines.

- **Portable high-pressure tap sampling:** The uppermost configuration on Figure 5.18 is a high-pressure zone where a ball valve or needle valve is installed and the outlet is fitted with a piece of stainless steel helical tubing. The purpose of the tubing is to reduce the pressure of the fluid to a safe level before it enters the sampling bottle. A similar effect can be achieved using a small, hand-held pressure-reduction valve.
- **Minimess tap sampling:** This option requires the installation of a minimess valve or similar sampling valve, preferably on an elbow. Minimess valves are probe-style valves commonly used for oil analysis and pressure diagnostics. The sampling bottle has a tube fitted with a probe protruding from its cap. The probe attaches to the minimess valve, allowing the oil to flow into the bottle. There is a vent hole on the cap of the sampling bottle so that when the fluid enters the bottle the air can exhaust. This particular sampling method requires lower pressures (less than 500 psi) for safety.

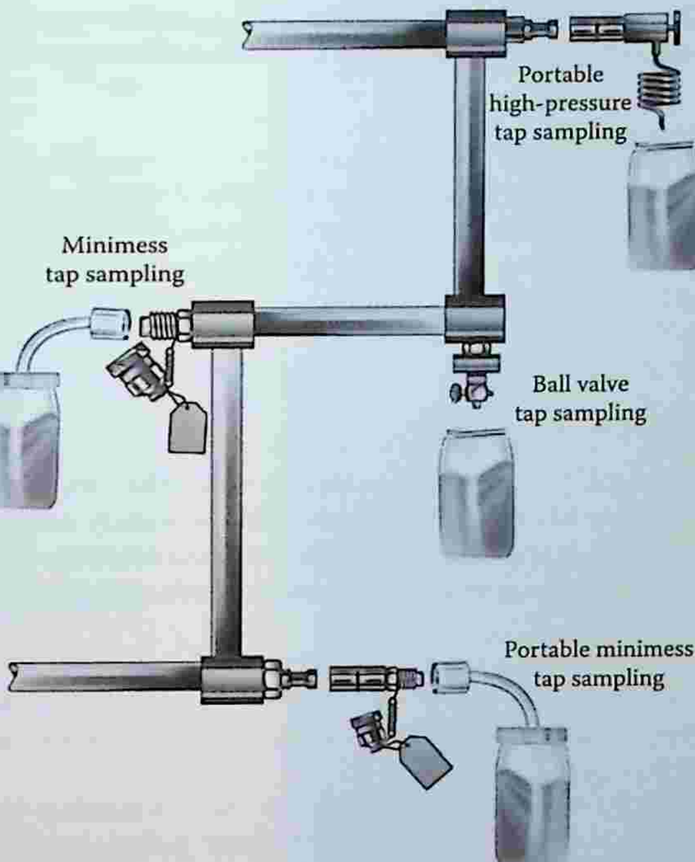


FIGURE 5.18 Options for sampling pressurized lines.

- **Ball valve tap sampling:** This configuration requires the installation of a ball valve or one of many closely-related valves specific for oil sampling. They are typically actuated by push-button or knob rotation to extract the fluid sample. When sampling, the valve should be opened and adequately flushed. Extra flushing is required if the exit extension from the valve is uncapped. Once flushed, the sample bottle's cap is removed and a sample is collected from the flow stream before closing the valve. Care should be taken when removing the bottle cap to prevent the entry of contamination. This technique is generally not suitable for high-pressure applications.
- **Portable minimess tap sampling:** This option requires installing a minimess valve onto the female half of a standard quick-connect coupling. This assembly is portable. The male half of a quick-connect is permanently fitted to a pressurized line of the system at the desired sampling location. To sample, the portable female half of the quick-connect is screwed or snapped (depending on adapter type) onto the male piece affixed to the machine. As the adapter is threaded onto the minimess valve, a small spring-loaded ball is depressed within the minimess valve, thereby allowing oil to flow through the valve and into the sample bottle. In many cases, these male quick-connect couplings are pre-existing on the equipment. A helical coil or pressure reduction valve, previously described, should be used on high-pressure lines for safety reasons.

5.8.3 Sampling from Low-Pressure Circulating Lines

Occasionally a return line is not sufficiently pressurized to take a sample. In such cases, sampling requires assistance from a vacuum pump equipped with a special adapter allowing it to attach momentarily to a sampling port, such as a minimess valve. With the adapter threaded onto the minimess valve, fluid can then be drawn by vacuum into the bottle (Figure 5.19) [10,16–18].

5.8.4 Drop-Tube Vacuum Sampling

One of the most common methods for sampling sumps and reservoirs is to use the drop-tube vacuum sample method. A tube is inserted through a fill port, hatch or dipstick port and lowered into the fluid, usually about midway into the oil level. This sampling method has a number of drawbacks and should be avoided if the sampling methods previously described can be applied instead.

5.8.5 Sampling Bottles and Hardware

An important factor in obtaining a representative sample is to make sure that the sampling hardware is completely flushed prior to obtaining the sample. This is usually accomplished using a spare bottle to catch the purged fluid. It is important to flush five to ten times the dead space volume before obtaining the sample. All hardware in which the oil comes into contact is considered dead space and must be flushed, including:

- System dead-legs,
- Sampling ports, valves and adapters,
- Probe on sampling devices,

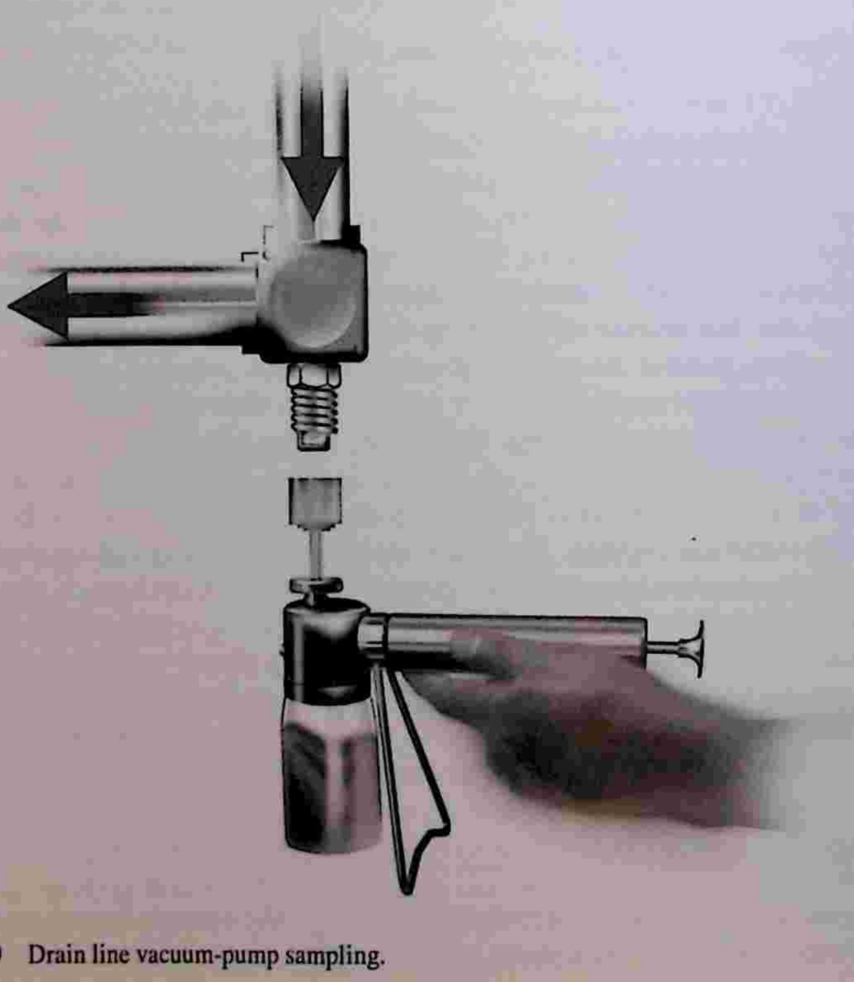


FIGURE 5.19 Drain line vacuum-pump sampling.

- Adapters for using vacuum sample extraction pumps,
- Plastic tubing used for vacuum pumps (this tubing should not be reused to avoid cross-contamination between oils).

There is an assortment of sampling bottle types that are widely used in oil analysis. An appropriate bottle needs to be selected for the application and the test slate that is planned. Several features, including size, material and cleanliness must be considered when selecting a sample bottle [10,16–18].

Bottle material. Modern sample bottles are made of PET plastic (polyethylene terephthalate) due to their chemical compatibility with most base oils and additives, along with the fact that they are clear, strong (fracture resistance), inexpensive, and widely availability. The primary disadvantage of using PET bottles is the risk that they will melt or become soft when sampling high temperature fluids, say above 200°F.

Bottle size. Bottle size should correspond directly to the minimum amount of fluid specified by the laboratory or onsite instrument(s). This volume should be sufficient to:

- Perform the routine test slate;
- Repeat one or two tests in the event of aberrant data;
- Perform exception tests (e.g., ferrography) triggered by a routine test such as a particle count;
- Leave a sufficient residual amount for retesting (confirmation testing) in the future, if required (these are often called “retains”).

Bottle cleanliness. The sample bottle cleanliness requirement is dependent on the target cleanliness of the hydraulic fluid. Modern oil analysis programs typically specify that bottles be ten times cleaner than the fluid target cleanliness for the same volume. The nomograph in Figure 5.20 is helpful in defining bottle cleanliness requirements [1].

5.8.6 Sampling Frequency

The use of scheduled sampling intervals is common in lubricant and hydraulic fluid analysis. The sampling frequency is generally tied to oil drain intervals, operating hours or usage events. Standard recommended intervals reported by OEMs, laboratories, and in technical literature are often used initially as a default frequency. These intervals can be later adjusted based on experience, or customized, by taking into account the following machine and application-specific conditions [10]:

- Consequence of failure: Safety, downtime costs, repair costs, and general business interruption costs should be considered.
- Operating environment: Operation and fluid environment conditions influence the frequency and rate of machine and fluid failure. Among other factors, these include pressures, loads, temperature, speed, contaminant ingression rate, and duty cycle severity.
- Lubricant age: In many cases problems occur right after lubricants are serviced (drains and refills). A problem can be associated with the accidental entry of the wrong oil and an incompatible oil. Hydraulic fluids approaching the end of useful life are also high risk. Aged oils will often have depleted additives, incipient oxidation, and high levels of various types of contaminants.
- Machine age and maintenance factors: For most machines the chances of failure are greatest during break-in and after major repairs, rebuilds, and extended downtime. The risk may also increase as a machine approaches the end of its expected life.

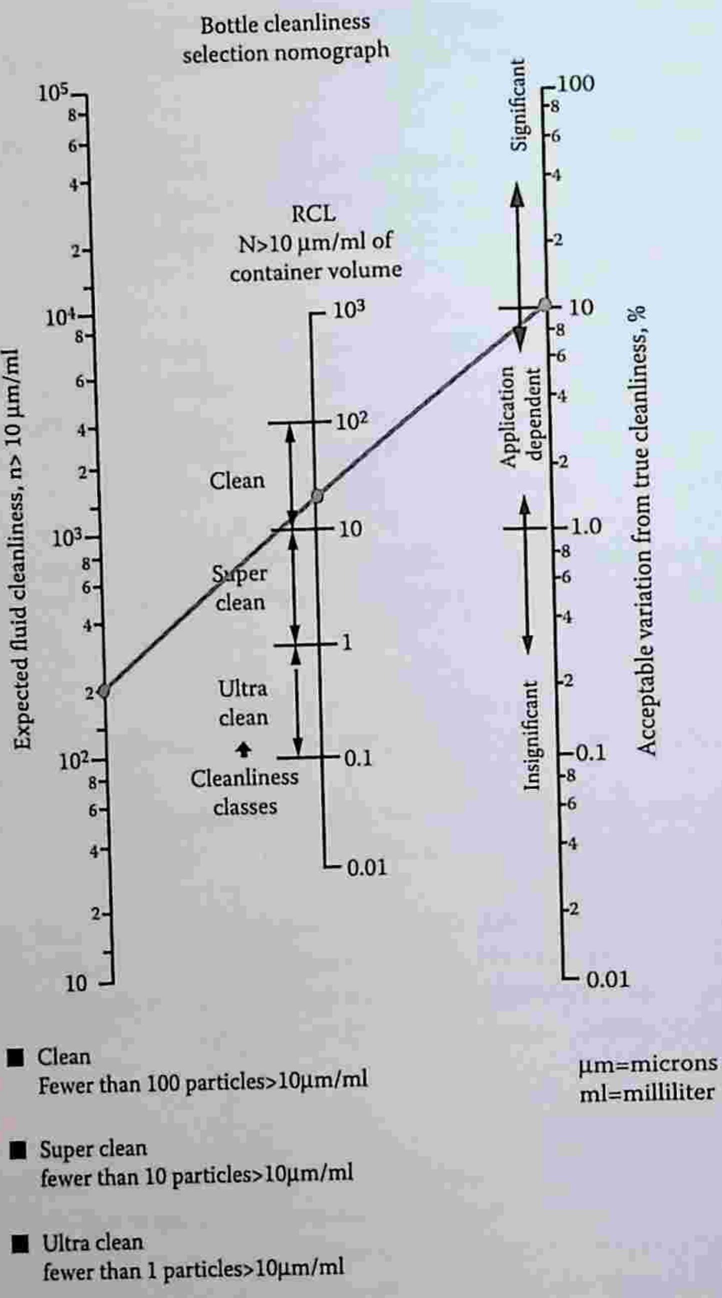


FIGURE 5.20 Nomograph for specifying required bottle cleanliness.

5.9 QUANTIFICATION AND CHARACTERIZATION OF PARTICLES

When particle contamination is monitored and reported routinely, not only is proactive maintenance generally achieved but also many of the goals of predictive maintenance. As such, particle counting (and other similar methods) is an important first line of defense in machinery reliability. Because of its value, it is not uncommon to find organizations testing the cleanliness of their oils as frequently as once a week, especially for high-criticality machines.

The following are common proactive and predictive uses for particle counting and analysis in condition monitoring [19]:

Proactive Maintenance:

1. Routinely verify that in-service oils are within targeted cleanliness levels.
2. Check the cleanliness of new oil deliveries.

3. Quickly identify failed or defective filters.
4. Confirm that seals and breathers are effectively excluding contaminants.
5. Confirm that systems are properly cleaned and flushed after repair.
6. Confirm that new hydraulic systems are cleaned and flushed before use (roll-off cleanliness).
7. Identify the improper use of dirty top-up containers and poor maintenance practices.
8. Identify the need and timing for portable filtration systems.

Predictive Maintenance:

1. Identify early-stage abnormal machine wear.
2. Identify the location/source of abnormal wear by multi-point isolating methods.
3. Verify the effectiveness of corrective maintenance and botched repair jobs.
4. Monitor machine break-in progress by wear particle generation.
5. Identify abnormal rust and corrosion debris generation.
6. Serve as an effective screen for wear debris analysis (e.g., analytical ferrography).

5.9.1 Particle Monitoring and Analysis Methods

The following are the most significant and effective particle monitoring and analysis methods commonly used in the oil analysis field:

Particle counting. Particle counting is considered to be one of the most valuable test methods in fluid analysis and its use dates back to the 1960s. The particle count test reports the number of particles above specified size ranges (in microns) per fluid volume (usually per ml or 100 mL). Also, particle concentration and distribution data may be expressed in terms of ISO 4406:99 Cleanliness Codes (Figure 5.8) or by other less frequently-used codification systems, such as the revised SAE AS 4059E (formerly NAS 1638). Particles can be counted manually using optical microscopy (ISO 4407 and ASTM F312-97). In this method an aliquot of fluid is passed through a membrane. Afterwards, particles on the membrane are manually counted under a microscope. The method is similar to the patch test procedure discussed below. There are commercial methods available which enable membranes to be optically scanned and digitally analyzed for particle size, count and shape [20].

Most laboratories use automatic particle counters, which can report a particle count or ISO Code in just a couple of minutes. The two methods are laser optical (ISO 11500) particle counters and pore-blockage (BS 3406 & ISO/DIS 21018). Optical particle counters direct a laser light source at passing particles in the sensor cell [21], see Figure 5.21. The amount and frequency of light blockage is measured by a photodiode. This signal is converted to particle size and count by the use of standardized calibration methods. Pore-blockage particle counters use calibrated screens through which the sample flows during a test (Figure 5.22). The profile of the pressure rise or flow decay, caused by particle blockage of the screen's pores, is measured [22]. This profile is mathematically converted to an estimated particle count or ISO Code [23]. Some modern particle counting technologies also have the ability to characterize particle shape. With this added information, interpretation of the source, type, and severity of the particles can be estimated [24].

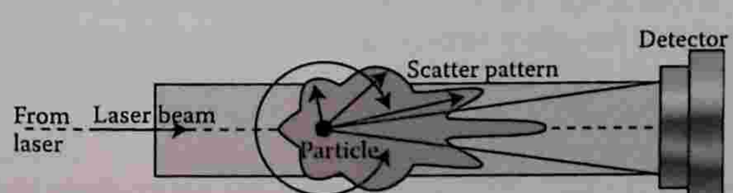


FIGURE 5.21 Light-blockage particle counter.

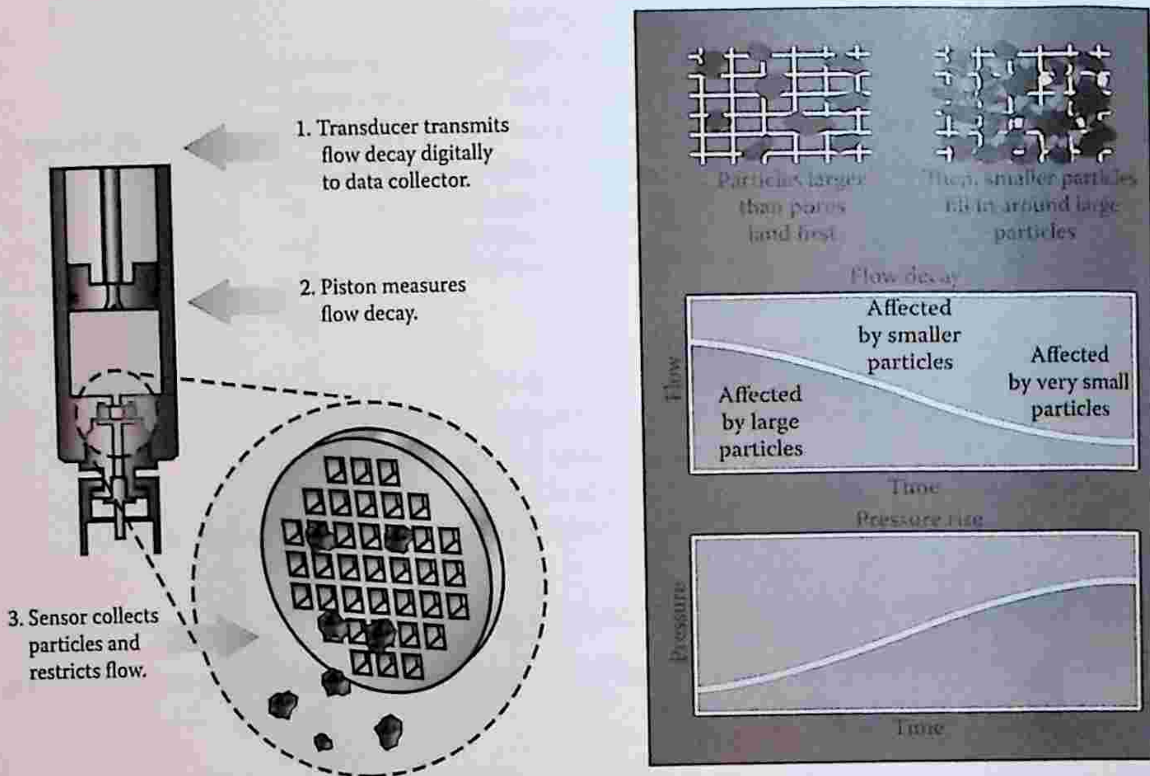


FIGURE 5.22 Pore-blockage particle counter.

Because of the differences between particle counting methods (manual, laser and pore-blockage), as expected, there will be differences in results on the same samples. The reasons for this are many and should not be a point of major concern for users if sample preparation and instrument procedures are used correctly. These methods are not absolute measurements, but instead estimate size and concentration using standard practice and assumptions. Regardless of the method, it is recommended that the same one is always used in order to ensure that results are consistent and repeatable. In the right application with the right procedure, most methods are very suitable in the context of maintenance and machine reliability [1,25,26].

Ferrous density. A sudden and significant increase in the population of large (greater than 5 μm) ferrous particles can signal the presence of an abnormal wear condition and perhaps of impending component failure. Contamination, poor lubrication and adverse mechanical conditions are the usual causes of high ferrous particles. Typically, at least one surface in a frictional pair is ferrous (iron or steel) and it is usually the surface most critical to machine reliability. For this reason the monitoring of ferrous particle density in used lubricants can provide valuable machine-health information. The need is further magnified by the fact that elemental analysis becomes less accurate with larger size particles (larger than 5 μm), which is usually the critical size range in monitoring and detecting impending failure.

Several instruments and methods are used by onsite and full-service laboratories for determining the concentration of ferrous debris. These methods are typically only able to detect concentrations of ferro-magnetic particles, but others employing the magnetic-induction principle can quantify non-ferrous metal particles as well. The ferrous density measurement units reported by laboratories vary by instrument type [10,25,26].

Elemental spectroscopy. Elemental spectroscopy quantifies the presence of dissolved and some undissolved inorganic materials by element in the lubricant (both oil and grease). Most elemental spectrometers used today for lubricants and hydraulic fluid analysis are the atomic emission type.

either Inductive Coupled Plasma (ICP), or Rotating Disc Electrode (RDE). These instruments work by exposing the sample to extreme temperatures generated by an arcing electrode (ASTM D6595) or by an argon plasma torch (ASTM D5185). The extreme heat vaporizes the atoms, causing them to emit energy in the form of light. Each atomic element emits light at specific and characteristic frequencies. The spectrometer quantifies the amount of light generated at each frequency (spectral line) and calculates the concentration of each element (iron, lead, tin, etc.) in parts per million (ppm) based on calibration curves.

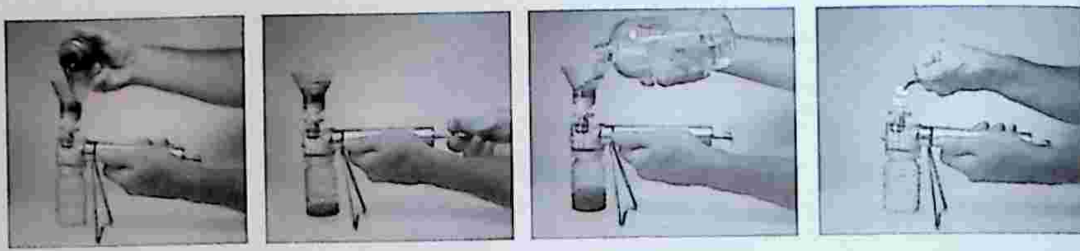
Most elemental spectrometers report the concentration of 15 or more elements. The elements reported can provide an indication of increased generation of wear debris, ingression of various types of contamination or depletion of certain additive elements (see Table 5.4). Dissolved metals and suspended particles up to approximately 2 μm are detected with high accuracy. The accuracy diminishes as particle size increases to more than 2 μm. Elemental concentrations can be greatly understated for particles larger than 5 μm.

It is important that critical machines have metallurgical maps which show where elemental families (unique groups of elements) typically emerge during wear and corrosion. Additionally, elemental data from close-proximity contaminants should also be characterized in terms of their major, minor, and trace elements that can be used as markers for identification purposes [10,25,26].

Microscopic contaminant and wear particle identification. When abnormal wear metals have been identified by other methods, including particle counting, elemental spectroscopy, and/or ferrous density analysis, a common and important exception test to perform next is the microscopic particle examination and identification. The most common version of the procedure is referred to as "analytical ferrography". Analytical ferrography involves the analysis of debris deposited onto a ferrogram slide or alternatively a filtergram membrane. Analysis of particle morphology (shape), color, size, reflectivity, surface appearance, edge detail, angularity, elemental content, and relative concentration provides the analyst with clues about the nature, severity and root cause of the contaminant ingression or wear problem. Scanning Electron Microscopy (SEM) can also used to examine particles as well as their elemental composition using an Energy Dispersive Spectroscopy (EDS) feature [27].

TABLE 5.4
Common Elements Found in Lubricants and Hydraulic Fluids

Element	Wear	Contamination	Additive
Iron (Fe)	X	X	
Copper (Cu)	X	X	X
Chromium (Cr)	X		
Tin (Sn)	X		
Aluminum (Al)	X	X	
Lead (Pb)	X		
Silicon (Si)		X	X
Sodium (Na)		X	X
Boron (B)		X	X
Calcium (Ca)		X	X
Magnesium (Mg)		X	X
Zinc (Zn)	X		X
Phosphorous (P)		X	X
Molybdenum (Mo)			X
Potassium (K)		X	



1. Introduce sample with solvent into patch-making funnel

2. Pull vacuum to transfer fluid through patch

3. Rinse with solve

4. Remove patch for inspection

FIGURE 5.23 Patch preparation sequence.

Although largely a qualitative technique, the analyst typically reports the presence and concentration of wear particles, friction polymers, dirt and sand, fibers, and other solid contaminants on either a 1 to 10 or a 1 to 100 scale in order to illustrate severity. Descriptive text and photomicrographs usually accompany the enumerated values to clarify conclusions and recommend corrective actions.

It is important to determine the root cause of machine failure and abnormal wear problems so they can be eliminated, thus avoiding recurrence. By combining information from analytical ferrography with other lubricant analysis and maintenance technology evaluations, the analyst attempts to answer the following questions [10,25,26,28]:

- Where in the machine does the contaminant or wear debris originate?
- What is causing it (forcing function)?
- How severe or threatening is it (residual life)?
- Can the condition be mitigated or arrested without downtime or loss production?

Patch Test. This method is similar to microscopic contaminant and wear particle identification. A small amount of sample is pulled by vacuum through a porous membrane (typically around 5 μm) to enable suspended particles to become deposited on the membrane's surface. A solvent is used to rinse any residual oil from the surface of the membrane (Figure 5.23). Afterwards the

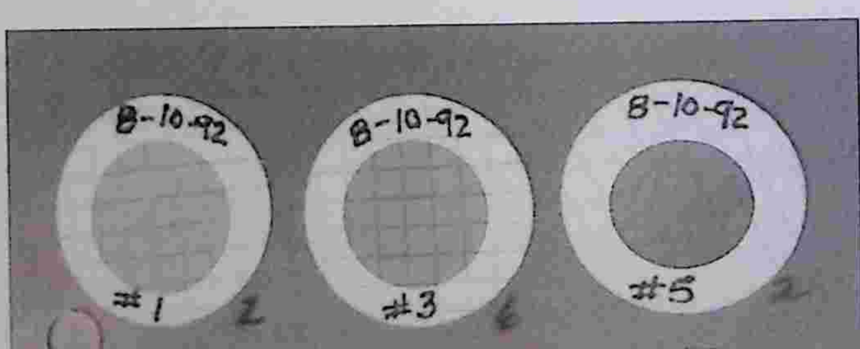


FIGURE 5.24 Patches of varying colors and densities.

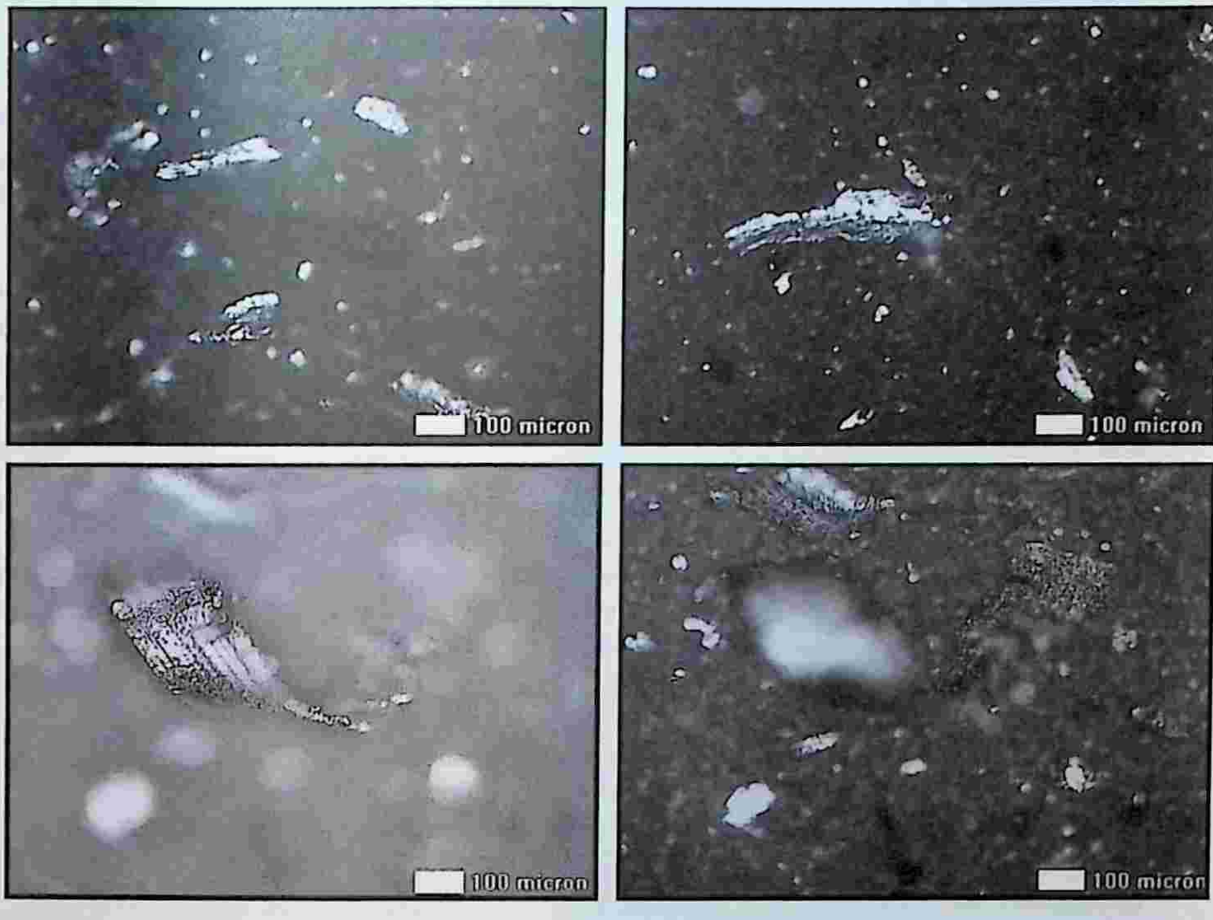


FIGURE 5.25 Patch images under magnification.

membrane can be visually inspected for overall particle density and color (Figure 5.24) [28]. If an abnormal debris field is encountered then the membrane can be placed under a top-lit microscope for a detailed analysis and characterization of the particles (Figure 5.25) [29]. Many analysts will estimate the fluid's ISO Code (ISO 4406:99) based on the overall appearance of particles, sometimes using comparator standards. One such comparator standard used in patch analysis of aviation fuels is discussed in Appendix A3 of ASTM D2276 and is easily applied to hydraulic fluids as well. However, unlike optical particle counters, patch testing allows particle shape, color, edge detail, and organic particles to be inspected. In addition, unlike analytical ferrography, patch testing is relatively inexpensive and can easily be performed in the field [29].

Blotter spot test. This simple test, also known as "paper chromatography" or "radial planar chromatography," is used to examine soft insoluble suspensions in oil using blotter paper to which a small aliquot of sample is applied. Varnish-producing impurities will form distinction deposits and rings on the blotter paper as the oil wicks outward in a radial direction by capillary action. These impurities include carbon insolubles, oxide insolubles, additive degradation products, and glycol contamination. This is a good quality field and laboratory test [10,30].

Ultracentrifuge and other varnish-potential tests. These methods use centrifugation or coagulation to separate and estimate the concentration of varnish-producing oxide-insolubles and other soft impurities in hydraulic fluids and other oils. Various methods are currently used by oil analysis labs [31].

5.10 DATA INTERPRETATION AND TROUBLESHOOTING

The following are common examples of different data-alarming strategies used in lubricant analysis. To one extent or another all of these strategies have an application in the analysis and interpretation of solid particle contamination in hydraulic fluids. When used together, across several testing schemes, early detection and diagnosis of data anomalies can be easily achieved [32].

- **Goal-based limits:** These are targets applied to fluid parameters like contamination to achieve machine life extension. Target cleanliness levels, as previously discussed, are goal-based alarms. For example, a hydraulic machine running at ISO 18/15 (per ISO 4406:99) cleanliness may experience a triple life extension if the fluid is cleaned to an improved ISO 15/12. Setting the limit at ISO 15/12 is a goal-based strategy; the goal being increased component service life. This type of limit is usually applied to particle count, moisture level (e.g., ASTM D6304), glycol level (e.g., ASTM D4291), fuel dilution, Acid Number (AN) (e.g., ASTM D664), and other common root cause conditions. The setting of such limits is highly dependent on the reliability goals of the equipment owner.
- **Aging limits**: Another type of limit or alarm relates to the progressive aging of a lubricant or hydraulic fluid. From the moment that a fluid is placed in service, its chemical and physical properties transition away from the ideal (i.e., those of the newly-formulated oil). Some properties transition very slowly, while others transition more dynamically. Limits keyed to the symptoms of lubricant deterioration are referred to as "aging limits". Aging limits can be effectively applied to such parameters as acid number, viscosity, oxidation stability tests (e.g., ASTM D2272), elemental spectroscopy for additives, infrared spectroscopy (oxidation, nitration, sulfation, and additives) and dielectric constant. The collective use of aging limits helps to estimate the Remaining Useful Life (RUL) of the lubricant. The level of contaminants (root cause) in a lubricant has a great influence on the rate at which RUL decays (effect).
- **Rate-of-change alarms**: Rate-of-change alarms are typically set to measure properties that are being progressively introduced into the oil, such as wear debris or contamination. The add rate (change) can be calculated per unit of time, hours, cycles, and so forth. For example, a 100 ppm increase in iron over a period of 100 operating hours could be stated as one ppm per hour of operation. When the parameter is plotted against time, the rate-of-change (add rate) equals the current slope of the curve. Unlike level limits, rate-of-change limits ignore the absolute value of the data parameter, emphasizing instead the speed at which the level is changing. Rate-of-change limits are effectively applied to particle counting (unfiltered systems), elemental wear metals, ferrous density, AN and oxidation stability. It can also be effectively applied to monitor abnormal degradation of additives with elemental and infrared spectroscopy.
- **Statistical alarms.** For many years, statistical alarms have been used effectively in lubricant analysis. The practice requires the availability of a sufficient quantity of machine and application-specific historical data from which to draw meaningful statistical benchmarks. The statistical alarming approach is simple. A population mean and associated standard deviation are generated from the available data. The data from a sample is compared to the mean of the population. If the value falls within one standard deviation of the mean, it is considered normal. If it falls outside of one standard deviation from the mean, but within two standard deviations, it is considered a caution, or simply reportable. If the result exceeds two standard deviations, the value is considered in critical alarm as it is higher, or lower as the case may be, than 95% of the population. Should the value exceed three standard deviations, it is a critical alarm, as the value exceeds the ninty-ninth percentile of the historic population. Statistical alarming methods are commonly applied to ferrous density, elemental metals and other predictive lubricant analysis measurements.

5.10.1 Analytical Strategy for Detecting and Troubleshooting Common Problems

The following is a discussion of how oil analysis can be used to detect and troubleshoot particle-related problems that are commonly found in fluid samples. This methodology combines sampling strategy, onsite oil analysis tools, routine laboratory analysis, exception testing, inspections, and companion technologies.

Wear debris detection: When hydraulic systems and components are operating abnormally due to misalignment, fluid degradation, contamination, corrosive conditions, and so on, microscopic pieces of the system's components become suspended in the oil in the form of wear debris. Fluid analysis provides very early warning of this occurrence and increases the planning time and the number of options with which to troubleshoot and correct the problem.

Sampling Strategy	In close proximity to the wearing component or directly downstream of it.
Machine Inspections	Wear debris on filters, metallic sediment on tank bottoms, abnormal noise, high running temperatures.
Onsite Tests	Patch tests, particle counting, used-filter inspections, ferrous density tests.
Primary Lab Tests	Particle counting, ferrous density, elemental analysis.
Alarming Strategy	Statistical limits, rate-of-change, trend plots.
Exception or Confirming Tests	Analytical ferrography, patch testing, machine internal inspections.
Confirming Companion Technologies	Vibration, thermography.

Wear debris analysis. When an abnormal wear condition is encountered, it should be analyzed to provide an indication of the nature, severity, and root cause of the problem. This requires an investigation of the wear particles themselves along with a review of collateral information such as vibration analysis, operational information, lubricant analysis, system inspection, used-filter inspection, and so on.

Sampling Strategy	In close proximity to the wearing component or directly downstream of it.
Machine Inspections	Wear debris on filters, metallic sediment on tank bottoms, abnormal noise, high running temperatures.
Onsite Tests	Patch tests, particle counting, used-filter inspections, ferrous density tests.
Primary Tests	Analytical ferrography, elemental analysis.
Alarming Strategy	None, qualitative.
Exception, Supporting or Confirming Tests	Ferrous density, particle counting, elemental analysis of filter debris.
Confirming Companion Technologies	Vibration, thermography.

Solid particle contamination. An alarm on particle contamination, using ISO Codes—for instance, signals an increase in suspended particles due to such occurrences as the failure of a filter, ingestion of contaminants from the environment through seals, vents, new oil or an increase in the generation of wear debris.

Sampling Strategy	In close proximity to high-risk ingression points or directly downstream of them.
Machine Inspections	Sediment on tank bottoms, unsealed reservoirs/sumps, filters in bypass, defective breathers, etc.
Onsite Tests	Patch tests, onsite particle counter, used-filter inspections, ferrous density tests.
Primary Tests	Particle count, elemental analysis.
Alarming Strategy	Cleanliness targets (ISO Code, NAS, etc.) based on reliability goals.
Exception, Supporting or Confirming Tests	Patch tests, analytical ferrography.
Confirming Companion Technologies	None.

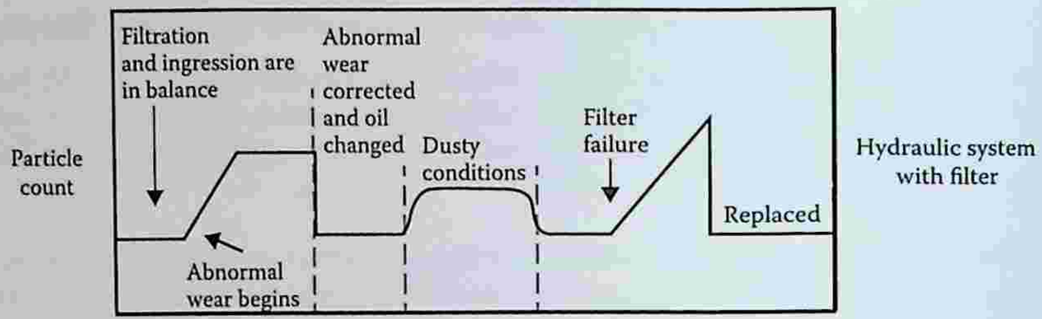


FIGURE 5.26 Typical particle count trends.

Figure 5.26 shows how particle count trends can vary over time. Because particle counters monitor particles in the general size range controlled by filters, particle concentration equilibrium (steady-state condition) is usually achieved—that is, particles entering the oil from ingression minus particles exiting from filtration will leave behind a steady-state concentration. When filters are properly specified and ingression is under control this steady-state concentration will typically be within the cleanliness target. For systems with no continuous filtration, or poor filtration, the equilibrium is usually not effectively established (there is no continuous or reliable particle removal). This can cause the particle concentration to be continuously rising, or moving erratically.

5.10.2 Troubleshooting a High Particle Count Result

High particle counts generally have one of four possible explanations and outcomes when investigated:

1. The system is not in any immediate danger; however, either a filter has failed or there is a new source of particle ingression. The problem is solved by correcting the offending filter or ingression source.
2. There is a new ingression source or filter failure and the machine is in immediate danger due to the resulting high particle count. This problem is solved by a rapid clean-up of the oil, followed by correcting the failed filter or ingression source.
3. The high particle count is due to abnormal wear particle generation constituting a potential threat to machine reliability. This can be solved by performing a root cause failure analysis followed by appropriate remediation and clean-up as required.
4. The high reading was due to sampling error (including dirty sample bottle), analytical error (particle counter calibration, sample preparation, etc.) or soft particles (dead additives, oxide insolubles, etc.) that were read as hard particles.

5.11 SUMMARY

Contamination control requires a critical amount of planning, preparation and deployment. It is sometimes referred to as "planned cleanliness". Success depends heavily on behavior-based strategies and execution. This fact is widely validated by the many case studies that have been published on this subject in recent years.

Some of the main elements for achieving planned cleanliness as discussed in this chapter are summarized below:

1. Educate organizational players and stakeholders on the virtues of cleanliness and the tactics for achieving it. This puts everyone on the same page, aligned with a single objective.
2. Keep target cleanliness for critical machines front and center—the more conspicuous, the better. Make ISO Codes a part of the company's reliability vocabulary. Put highly visible

cleanliness targets on, or near, machinery to which they relate. Communicate clearly the ways in which contamination control plays a strategic role in achieving business objectives.
3. Invest in onsite particle counting or patch testing. Install live-zone sampling ports to ensure representative samples. Monitor machine cleanliness vigorously. People work the metric, so make particle counting an important one. Talk it up and celebrate cleanliness at every opportunity.
4. Post green, yellow and red tags on all program machines to enunciate cleanliness status. Any fluid that is noncompliant gets a yellow or red flag (depends on severity) tagged to the machine until the aberrant condition is remedied. Take immediate action to correct non-compliant machines.
5. Pursue every reasonable opportunity to exclude contaminant ingression. Upgrade filtration prudently.
6. Put oil suppliers, workshop technicians, parts suppliers, and rebuild contractors on notice regarding roll-off cleanliness. Develop rigorous inspection procedures and follow through for all nonconforming oils or equipment.
7. Keep track of program costs and savings.

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