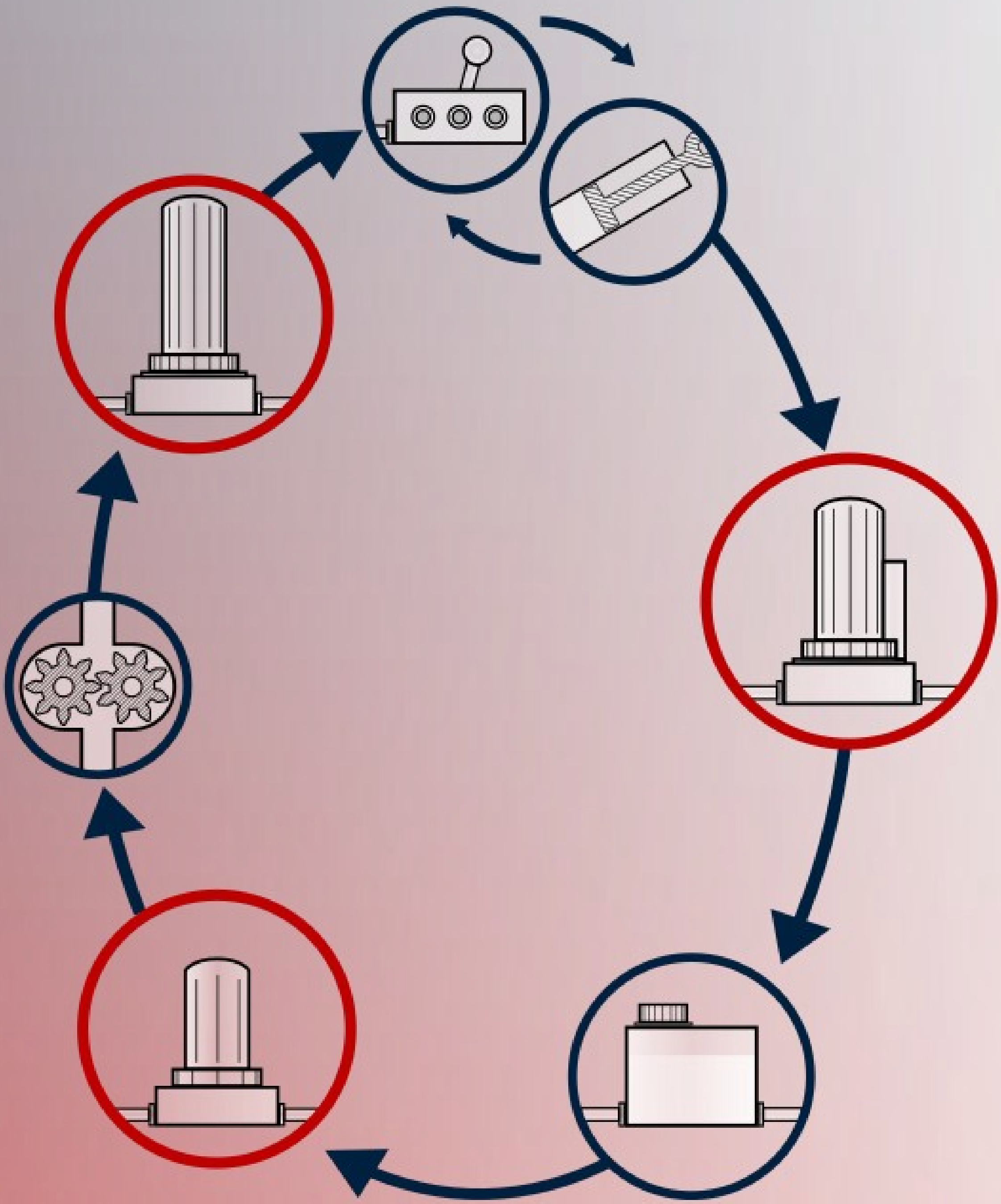
Hydraulics and Filtration



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For designers, manufacturers and users of hydraulic systems, it is important to be aware of the properties of hydraulic fluids, their contaminants and the common damages caused by contaminants to hydraulic equipment. These factors are crucial in effective design and use of filtration systems.

This handbook aims to serve as a general guide on hydraulic filtration systems, especially for persons with limited expertise on the subject.

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Chapter 1 – Basics

Hydraulics

Foundations of modern hydraulics were laid by Blaise Pascal and other scientists around the 17th century. However, those early principles could not be widely applied in practice until the advent of washers and proper sealing methods in the twentieth century. In the last fifty years, advances in technology and manufacturing have made possible more widespread use of hydraulic principles.

Hydraulic systems use water, oils or other fluids to transmit mechanical force. In addition to liquids, gasses can also be used in pressurized hydraulic systems such as presses and jacks. Hydraulic systems are used in a wide range of cases, from water canals to spaceships.

In general, Hydraulics is the study of the techniques concerning the transmission of mechanical force through liquids.

Figure 1- Some applications of hydraulic systems

Hydraulic Systems

Hydraulic systems are systems designed and built based on the principles of Hydraulics and are used to transmit force through fluids. There are many known advantages to these systems, including:

- Possibility of transmitting large mechanical forces
- Possibility of constant and precise re-adjustments of rate and efficiency even during operation
- Unrestricted rotational speeds
- Easily achievable changes in directions of movement and rotation
- Possibility of rapid and precise change of velocity
- Steady and stable movement of equipment
- Protection against overload

However, there are some disadvantages to using hydraulic systems, including:

- Change of fluid properties when heating
- High accuracy manufacturing requirements
- Sensitive sealing
- Mechanical forces being transferred in unwanted directions due to fluid properties

Moreover, the effects of internal friction in hydraulic fluids is one of the most important disadvantages of using these fluids. This type of friction can alter a fluid's physical and chemical properties and weaken sealing components.

Considering these points, it is very important to take special care and precaution in design, deployment and use of hydraulic systems.

Chapter 2 – Contaminant-caused Damages

Heat, assembly processes and contaminants together cause a very large portion of problems in hydraulic systems and their components. Problems caused by heat are usually related to design and manufacturing processes along with the materials used, while problems caused during assembly generally concern sealing and fittings. It is contamination that causes our greatest concerns for hydraulic systems. According to designers and users of these systems, only a quarter of the problems in hydraulic components are not caused directly by contaminants.

Entry of contaminants into a system can inflict heavy costs on the owners by causing serious disruptions to the core functions of hydraulic fluids. These functions are as follows:

- Acting as a force transmission medium
- Lubrication of inner moving parts
- Acting as a heat transfer medium
- Filling the gaps between moving components

If any of these functions are disrupted, the hydraulic system will not operate as intended. However, proper use and maintenance of fluids can help prevent unexpected downtime and thus save thousands of euros for production plants. Problems caused by contaminants can inflict a wide range of costs on a system:

- Costs of downtime
- Costs of component replacement
- Costs of fluid change
- Costs of fluid elimination
- Increased maintenance costs
- Increased amount of waste

Contaminant-caused damage usually occurs in the following forms:

- Clogging
- Component wear
- Formation of rust or other types of oxidation
- Formation of chemical compounds
- Altered properties of additives
- Bacterial growth

Hydraulic fluid maintains the space between moving components by forming a lubricating film. Ideally, this film is thick enough to fill component clearances. This keeps wear at low levels and increases component lifespan, which could reach up to several million cycles.

In Hydraulics, “clearance” is defined as the space between components, either moving or fixed. Clearances for different types of hydraulic components are determined based on component role and expected efficiency.

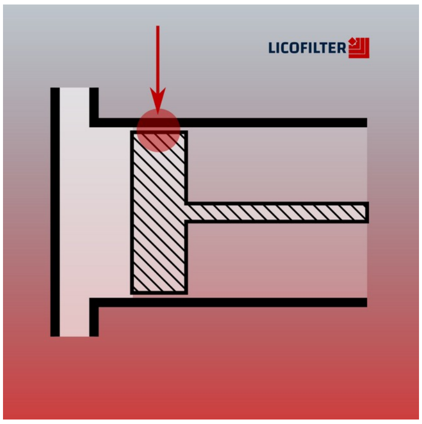

Figure 2- Clearance in piston pumps

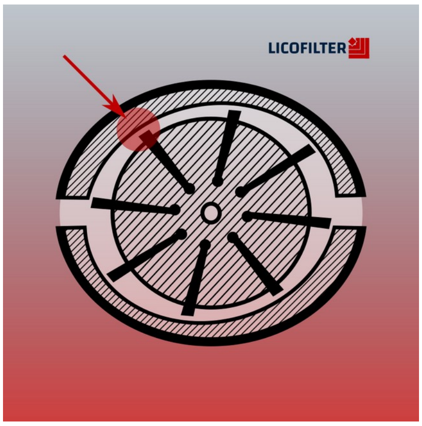

Figure 3- Clearance in vane pumps

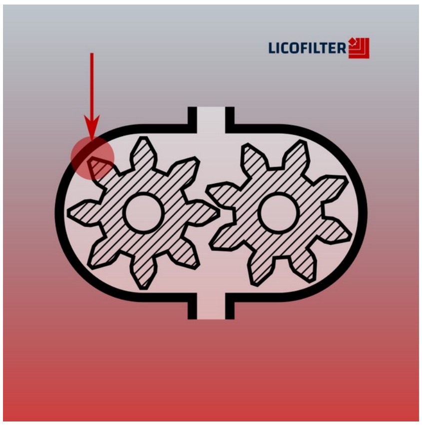

Figure 4- Clearance in gear pumps

Table 1 shows clearances for common hydraulic components:

Component	Clearance (microns)
Plain Bearing	0.5
Vane Pump (vane tip to outer ring)	0.5-1
Gear Pump (gear to side plate)	0.5-5
Servo Valve (spool to sleeve)	1-4
Hydrostatic Bearing	1-25
Piston Pump (piston to bore)	5-40
Servo Valve Flapper Wall	18-63
Hydraulic Actuator	50-250
Servo valve orifice	130-450

Table 1- Common clearances in hydraulics

Lubrication is achieved by introducing a film of lubricating fluid in the clearance. The thickness of this film depends on the designed clearance, the load under which the component operates, component velocity and lubricant viscosity.

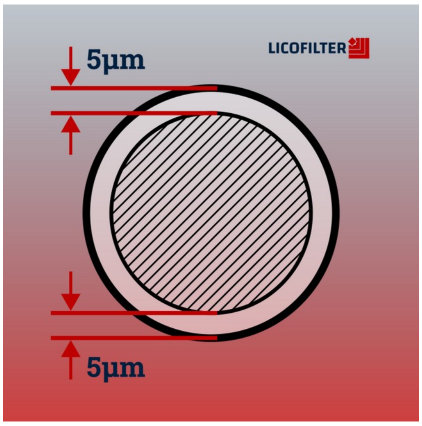

Figure 5- Component clearance by design

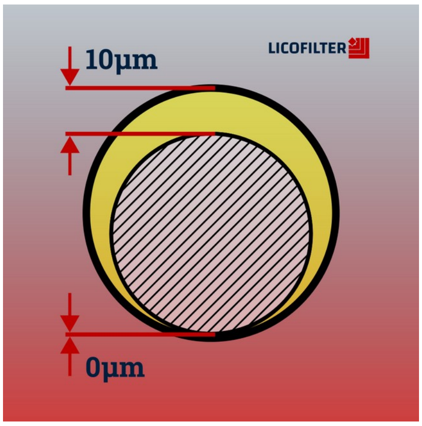

Figure 6- Clearance under load, without movement, with lubrication

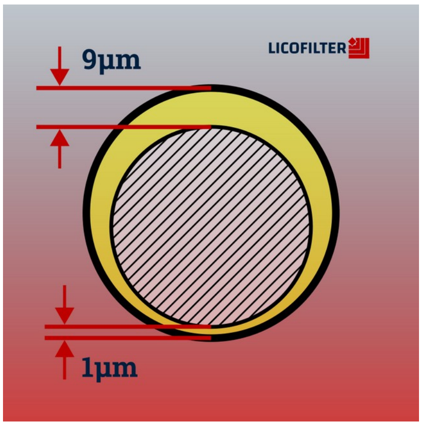

Figure 7- Clearance under load, during movement, with lubrication

Comparing component clearances with common particle sizes in *Table 2* can give a clear picture of how sensitive each hydraulic component is to various solid particles.

Particle or Range	Size	
	microns	inches
Grain of Common Salt	100	0.0039
Human Hair	70	0.0027
Lower Limit of Human Vision	40	0.0016
Flour	25	0.001
Red Blood Cells	8	0.0003
Bacteria	2	0.0001

Table 2- Relative particle sizes

Figure 8 on the next page illustrates the differences between these particles.

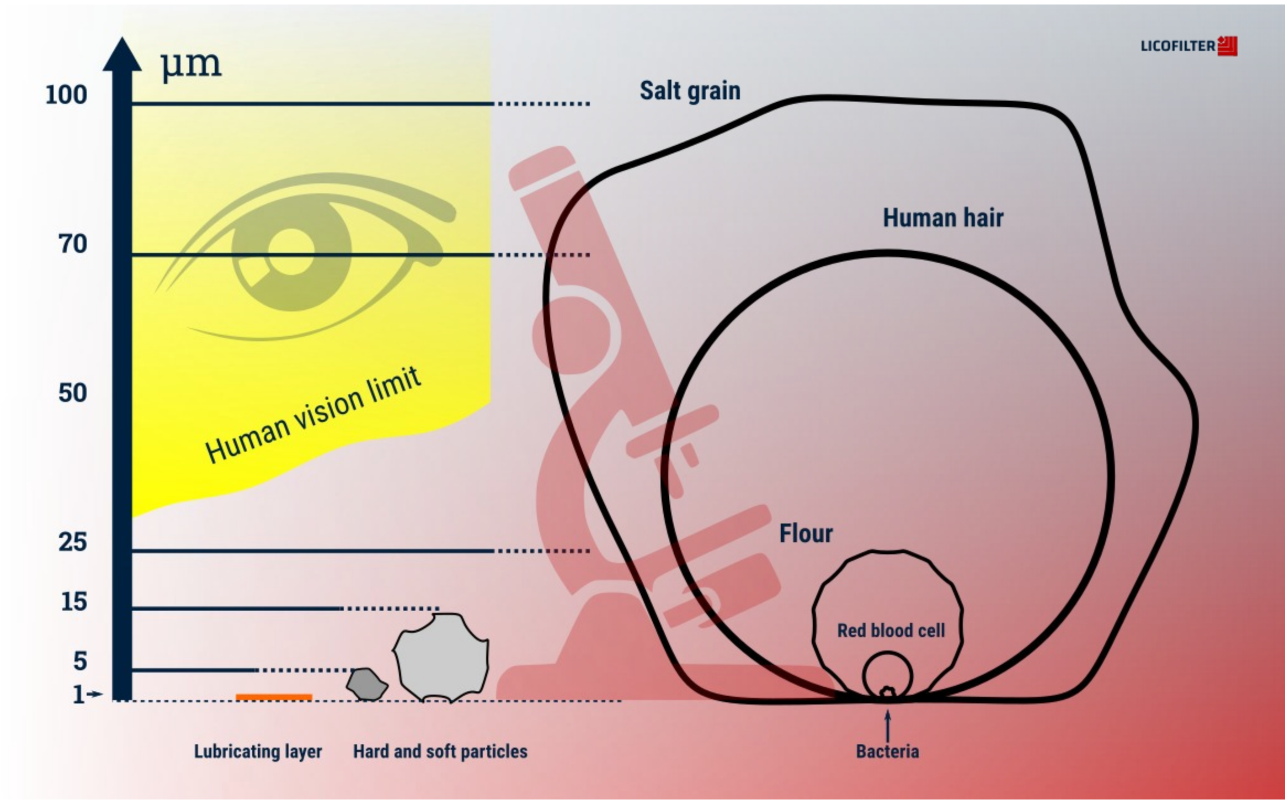

Figure 8- Comparison of particle sizes

Chapter 3 – Contaminant Types and Sources

There are three major types of contaminants of hydraulic systems:

- Solid Particles
- Water
- Air

This chapter will review these contaminants and common damages associated with each, along with ways of preventing those damages.

Solid Particles

Types

Solid particles are classified into two groups: “silt” (smaller than 5µm in diameter) and “chips” (larger than 5µm in diameter). While silt can cause defects in components over time, the presence of chips can cause immediate disastrous damage in a system.

Solid particles can also be categorized into the following groups:

1. Hard Particles

- **Silica:** These are crystalline particles with a high hardness value that exist naturally as quartz and sand. When the concentrations of silica particles in the environment is higher, the particles are more likely to enter the system and cause damage. Damage caused by silica particles is usually direct.
- **Carbon:** Carbon particles are commonly found as soot in work environments. These spherical particles tend to join together and form clusters. Carbon can cause damage to hydraulic systems directly or indirectly through chemical reactions with additives.
- **Metal:** Metal particles are found in various forms in hydraulic systems. These particles can enter the system or be produced in the system through wear caused by solid particles. Metal usually damages the system directly.

2. Soft Particles

- **Rubber:** Rubber particles are commonly produced in damaged areas of sealing washers. These particles damage the system directly if they find their way in.
- **Fibers:** Fibers commonly enter the system from the outside and cause direct damage.
- **Microorganisms:** Microorganisms are microscopic living organisms that enter the system through the fluid or other means. These organisms can grow inside the system and react with additives, which could create corrosive or otherwise damaging compounds.

As mentioned before, contaminants usually enter the system from the outside. It is important to note that solid contaminants can also cause indirect damage to the system. For example, formation of silt in fluids as a result of chemical reactions in deposited matter can highly alter fluid properties and deteriorate its quality.

Damages

Presence of solid particles in any part of hydraulic systems can cause different types of damage to these systems. Each of these types are discussed below:

Abrasion

When solid particles enter the space between two moving surfaces, they can cause abrasive wear on one or both of them. The amount of abrasive wear is dependent on the relative hardness of the particles and surfaces. The harder a particle is relative to a surface, the more abrasive wear it will cause on the surface.

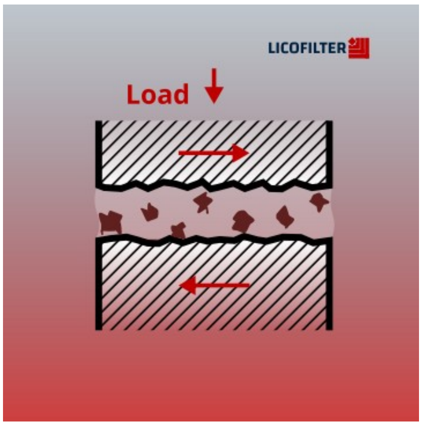

Figure 9- Abrasion in hydraulics

Erosion

When the fluid moves in high velocity, floating solid particles collide with the component's corners and inner walls and erode these surfaces over time.

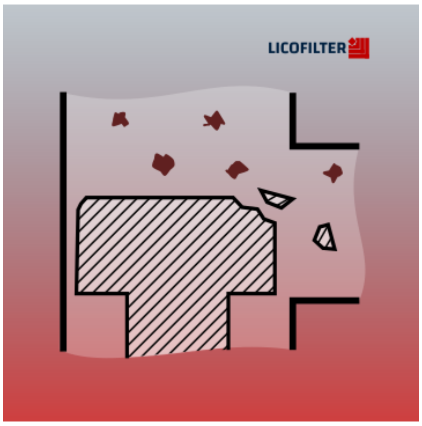

Figure 10- Erosion in hydraulics

Adhesion

Lack of proper lubrication between moving components can cause clumps of solid particles stick to components' inner surfaces. This will cause the surfaces to lose their evenness. It is noteworthy, that this is the only type of damage by solid particles which causes swelling. Other types of damage usually create cavities on surfaces.

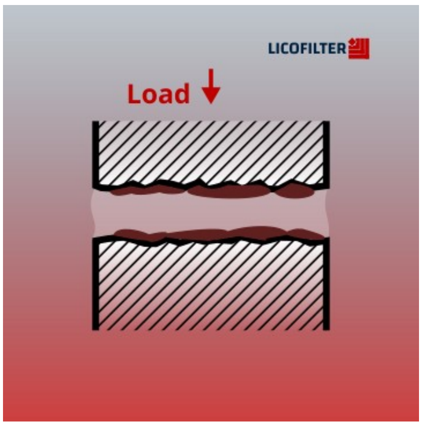

Figure 11- Adhesion in hydraulics

Fatigue

Constant impact of solid particles on inner surfaces causes surface stress to rise. With more impacts over time and more serious surface stress, small parts of surfaces are chipped away. These chips then enter the system and cause more damage over time.

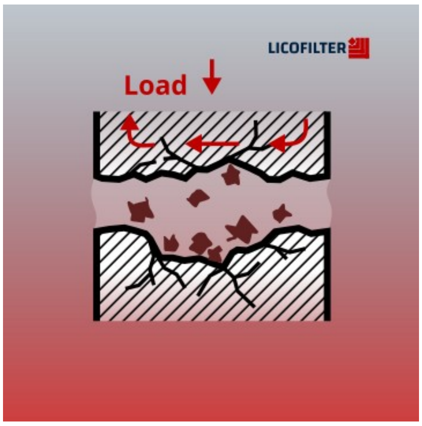

Figure 12- Fatigue in hydraulics

Corrosion

Some forms of solid contaminants such as microorganisms and soot particles chemically react with additives and form new compounds like acids, which will corrode surfaces.

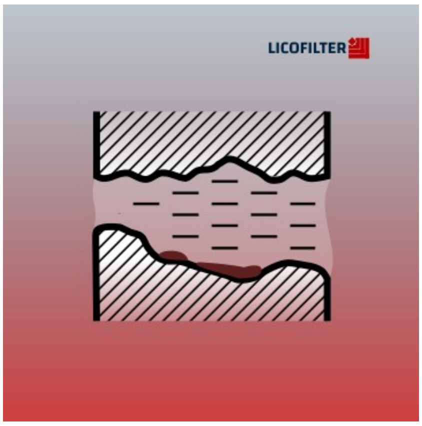

Figure 13- Corrosion in hydraulics

Damage Prevention

Solid particles can enter a system through different ways. For example, during the manufacturing, assembly, maintenance or operation of a system, new solid particles are created through abrasion, corrosion or similar processes. Moreover, solid particles can enter a system through leaking holes, enter with new fluid or in other similar ways.

The most important measure in restricting damage caused by solid particles is preventing their entry to the system in the first place. Separation methods such as filtration are more efficient when there are fewer particles in the hydraulic fluid.

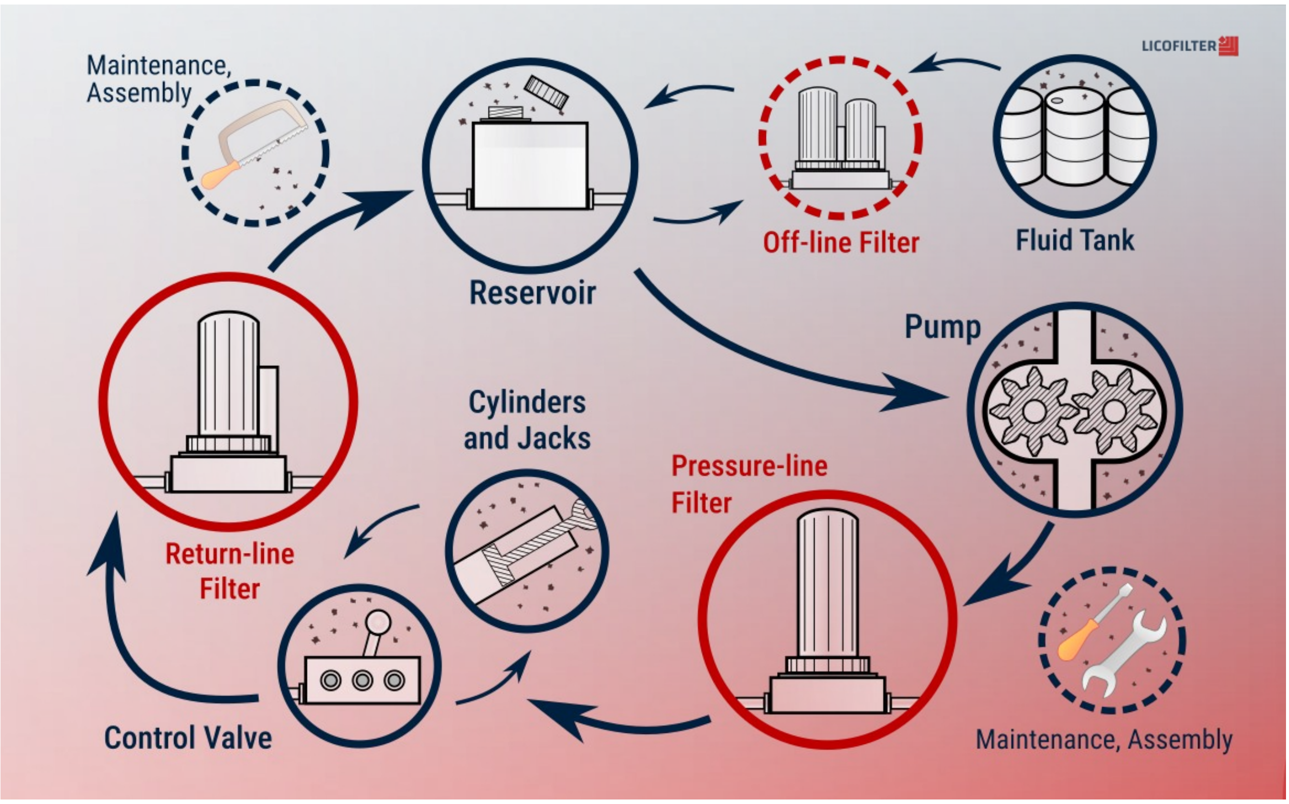

Figure 14- Hydraulic circuit contamination

Table 3 shows some typical ingression rates of particles into hydraulic systems in different environments.

Environment	Ingression Rate (per minute)*
Mobile Equipment	10^{8}-10^{10}
Production Halls	10^{6}-10^{8}
Assembly Facilities	10^{5}-10^{6}

Table 3- Ingression rates for common hydraulic equipment in different environments
** Number of particles larger than 10μm entering the system from various sources*

There are different measures for preventing solid particles from entering a system, including:

- Proper storage
- Use of breather filters on reservoirs
- Draining the fluid before the initial operation of the system
- Checking all seals periodically and replacing worn parts
- Covering all openings during maintenance
- Filtering the fluid before filling tanks

Preventing contaminants from entering hydraulic systems requires great care and attention. This must be taken into account in all units that employ hydraulic components.

Water

The hydraulic fluid normally contains 100ppm to 300ppm of dissolved water while keeping its color and clear appearance. More water content will make the fluid look cloudy and opaque.

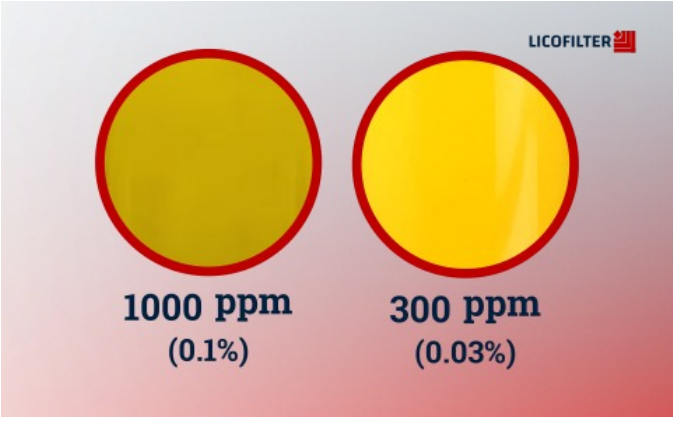

Figure 15- Effects of water on fluid appearance

Different fluids need different percentages of water content to reach their saturation point. This is shown in *Table 4*:

Fluid Type	Saturation Point (water content)	
	ppm	%
Hydraulic Fluid	300	0.03
Lubricant	400	0.04
Transformer Oil	50	0.005

Table 4- Water saturation points in common fluids

Damages

With the water content passing the saturation point in a fluid, its physical and chemical properties are altered. This can cause serious damage to the system, including:

- Corrosion of metal surfaces
- Increased abrasive wear
- Bearing fatigue
- Chemical decomposition of additives
- Fluid viscosity change
- Increased electrical conductivity

The presence of water can cause the lubricating film to become thinner and thus increase abrasion, especially in the presence of metals such as copper. Moreover, as the additives decline, corrosion of metal surfaces increase. The accelerated oxidation can lead to the formation of acidic sludge in the system and decrease the filtration efficiency. In transformer oils, excessive water content can increase electrical conductivity and thus increase the risks of electricity-related accidents. Therefore, it is crucial to carefully control the amount of water in hydraulic fluids.

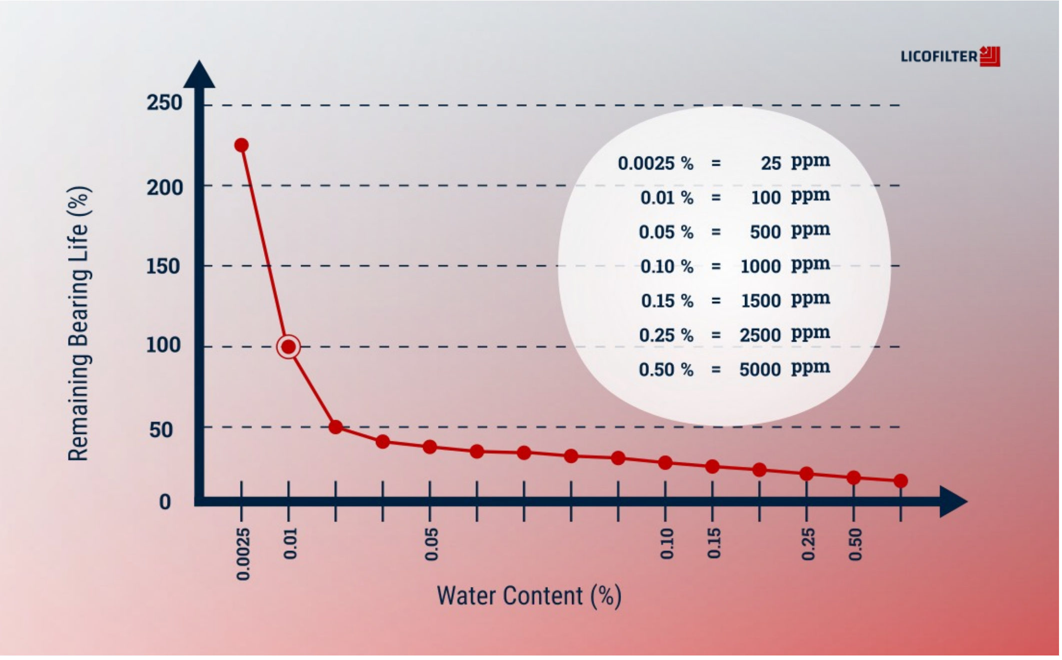

Figure 16- Bearing life affected by the amount of water in fluid

The graph above shows the estimated bearing life based on the presence of 100ppm water in the fluid. With more water content, bearing life is shortened and halved around the saturation point.

Damage Prevention

The following actions can be effective in preventing water from entering a system:

- Proper Storage
- Elimination of any leak in thermal converters
- Elimination of any leak in the reservoir inlet
- Replacing damaged seals

While these measures can prevent and reduce water ingression to some extent, water can always infiltrate systems or be produced through condensation inside reservoirs. In order to keep the water content at an acceptable level, there are three methods which are effective in separating water from the fluid:

- Use of water-absorbing filters (water separators)
- Spinning method (centrifugation)
- Use of vacuum dehydrators

Water is found in colloidal form in oils. This is the physical quality exploited by the methods above for separating water from hydraulic fluids. Water-separating filters are usually made of micro-fiberglass media. The special synthetic non-woven structure of these media separates water colloids from the fluid by absorbing them. The centrifugal method separates water particles by pushing them away from the fluid body in a spinning motion. The most effective and complete method, however, is vacuum dehydration, which vaporizes and separates water by creating a negative pressure on the fluid surface. Vacuum dehydration systems can be used as complementary measures in hydraulic systems.

Figure 17- A vacuum dehydrator

Air

The presence of air bubbles in the hydraulic fluid can disrupt the system and cause its efficiency to decrease considerably. This disruption can interfere with force transmission through the fluid. Damage caused by air entering hydraulic systems include:

- Cavitation
- Foaming
- Increased temperature
- Accelerated oxidation
- Reduced pump capacity
- Chemical reactions
- Less effective lubrication

In order to eliminate the destructive effects of air on hydraulic systems, it must be prevented from entering these systems in the first place. Methods for achieving this include:

- Providing proper head for the pump
- Opening and closing control valves slowly
- Ensuring the functionality of the reservoir cap
- Sealing all entrances to the system

As mentioned before, preventing contaminants from entering hydraulic systems is crucial and should be taken very seriously. As contaminants, water and air can reduce a system's performance heavily. Therefore, these contaminants must be taken care of, just as with solid particles.

Chapter 4 – Fluid Cleanliness

The hydraulic fluid, a fundamental part of every hydraulic system, is responsible for force transmission. Use of hydraulic fluid makes it possible to conveniently change the amount and direction of force by simply adjusting the flow, pressure or direction of the fluid, thus eliminating the need for many mechanical parts or processes.

In order to achieve an acceptable system efficiency and durability, the hydraulic fluid used should be in good condition. All the aforementioned types of contaminants, namely solid particles, water and air, can deteriorate fluid condition. Therefore, it is crucial to attempt to protect hydraulic systems from the damaging effects of contaminants, as much as possible.

In the first step, the type and amount of contaminants in the fluid should be determined. Solid particles are the most important of these contaminants. As the presence of contaminants in the fluid is inevitable, the International Standards Organization has published ISO 4406 for a standardized measurement of these contaminants. ISO 4406 provides a common protocol for determining fluid contamination level in terms of solid particle content.

In this chapter, we will review briefly the ISO 4406 standard and show how to determine the cleanliness code (also known as ISO-code) of a given fluid using a chart provided in the standard document.

ISO 4406

Based on this standard, a fluid is given a three-part code based on the severity of its contamination. Each part of the ISO 4406 code is based on a predefined size range of particles:

1. Particles larger than 4μm
2. Particles larger than 6μm
3. Particles larger than 14μm

For each range, the number of particles in the fluid are counted, and the final number is extracted from *Table 5*. The result will be three numbers, each of which indicate the contamination level regarding a specific particle size range.

Range	Minimum Number of Particles in 100ml	Maximum Number of Particles in 100ml
28	130,000,000	250,000,000
27	64,000,000	130,000,000
26	32,000,000	64,000,000
25	16,000,000	32,000,000
24	8,000,000	16,000,000
23	4,000,000	8,000,000
22	2,000,000	4,000,000
21	1,000,000	2,000,000
20	500,000	1,000,000
19	250,000	500,000
18	130,000	250,000
17	64,000	130,000
16	32,000	64,000
15	16,000	32,000
14	8,000	16,000
13	4,000	8,000
12	2,000	4,000
11	1,000	2,000
10	500	1,000
9	250	500
8	130	250
7	64	130
6	32	64
5	16	32
4	8	16
3	4	8
2	2	4
1	1	2
0	0.5	1

Table 5- ISO 4406 standard table

Determining Fluid Cleanliness

To gain a better understanding of how to determine the fluid cleanliness level using the table from ISO 4406, we will examine a sample fluid below.

The sample fluid contains 25,000 particles larger than 14µm, 420,000 particles larger than 6µm and 5,570,000 particles larger than 4µm. This would be based on lab counting. To determine the ISO 4406 code for this fluid, we will find the corresponding row for the number of particles in each size range and put the resulting number in the predefined position in the code template. Figures 18 through 22 illustrate the process. Figure 24 shows the final ISO 4406 code.

The ISO 4406 code is composed of three diameter ranges for counted particles. The ranges are:

- between 4µm and 6µm
- between 6µm and 14µm
- larger than 14µm

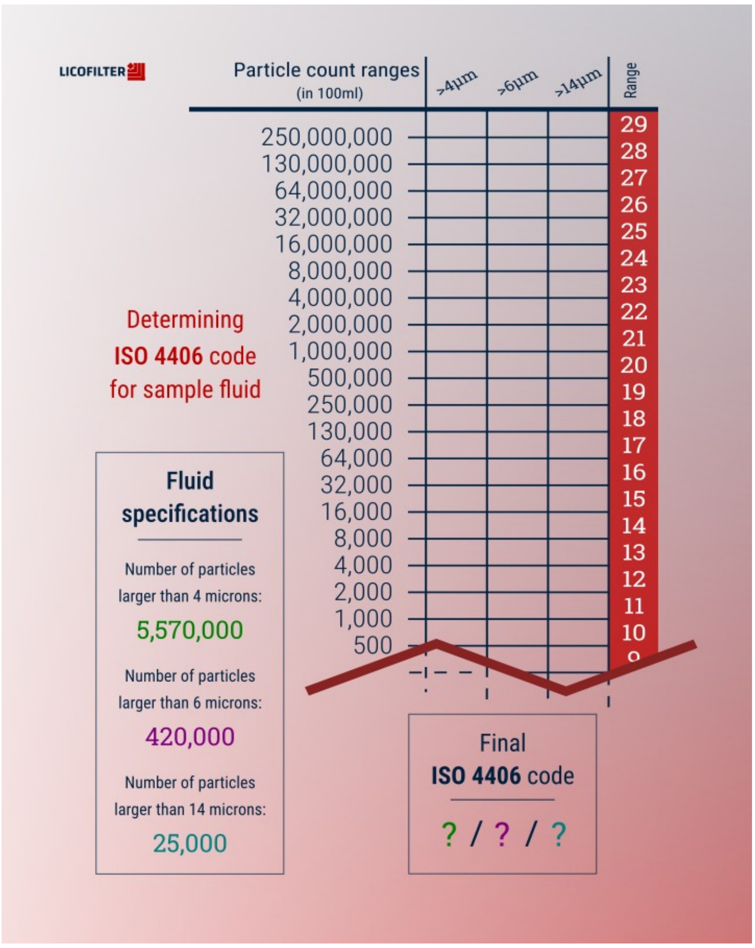

Figure 18- Determining the ISO 4406 level for the sample fluid

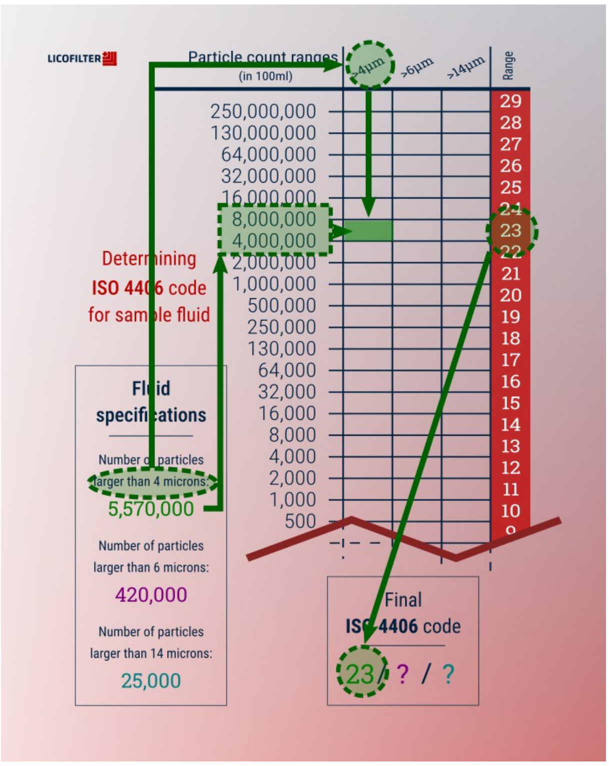

Figure 19- Determining ISO 4406 code – step 1: finding the number for particles larger than 4 µm

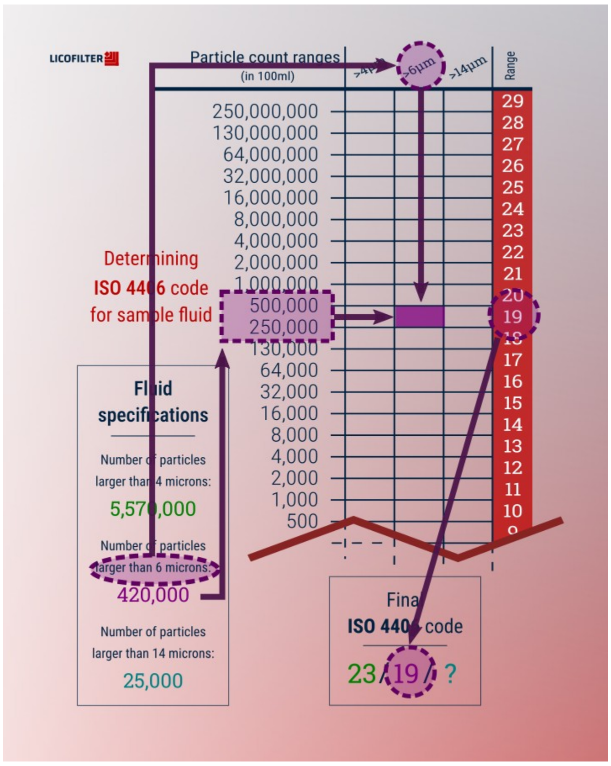

Figure 20- Determining ISO 4406 code – step 2: finding the number for particles larger than 6 µm

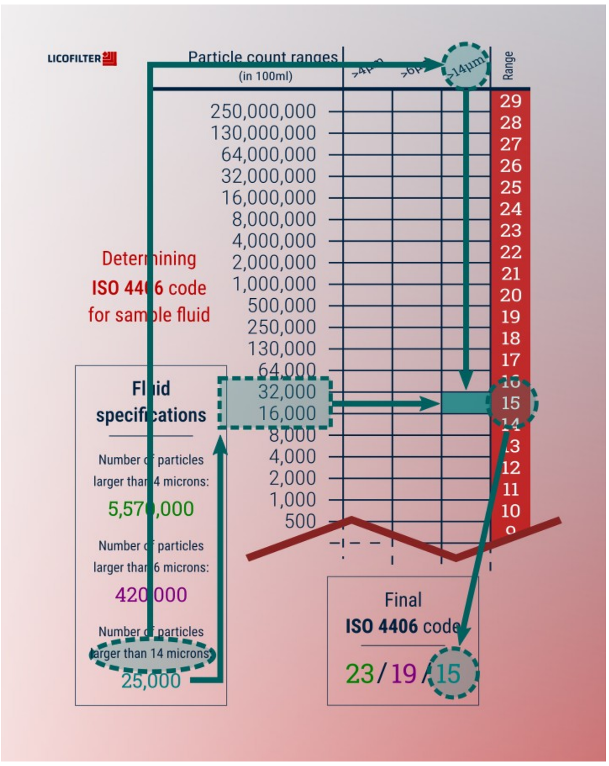

Figure 21- Determining ISO 4406 code – step 3: finding the number for particles larger than 14 µm

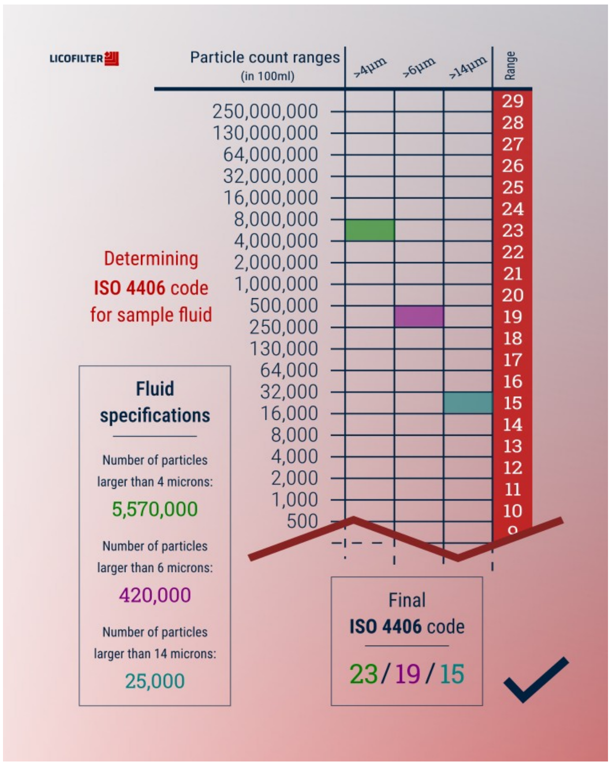

Figure 22- Determining ISO 4406 code – the resulting code for the sample fluid: 23/19/15

ISO Number	Particle Diameter (µm)	Particle Count Range (in 100 ml)
23	larger than 4	4,000,000 to 8,000,000
19	larger than 6	250,000 to 500,000
15	larger than 14	16,000 to 32,000

Figure 24- Sample fluid specifications

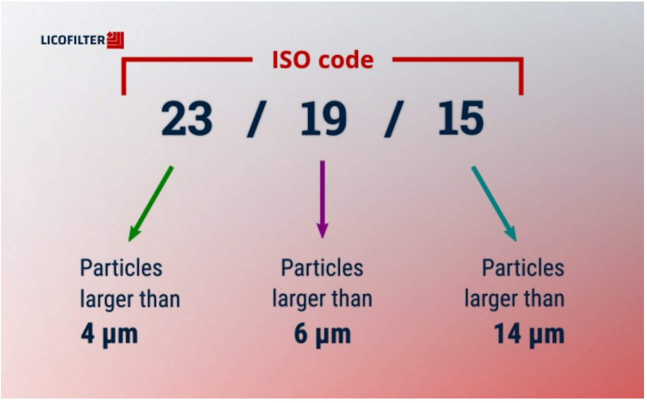

Figure 23- Sample fluid cleanliness level based on ISO 4406

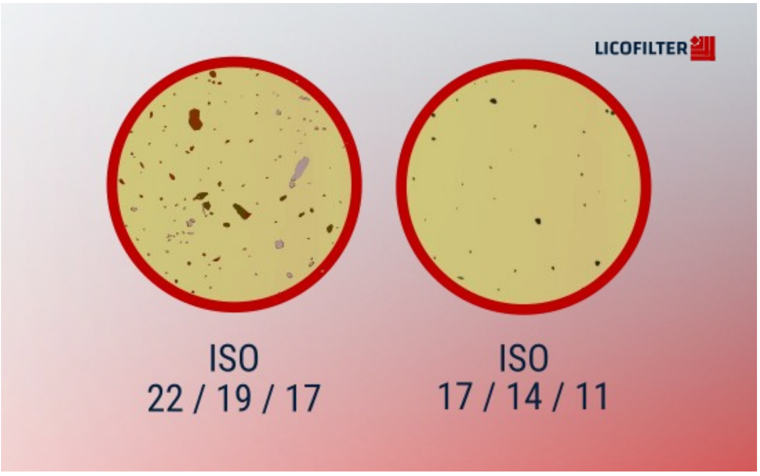

Figure 25- Comparison of two fluid samples with different cleanliness levels (~100x magnification)

Figure 25 illustrates two fluid samples with different contamination levels. The left sample contains more solid particles than the right sample.

Chapter 5 – Fluid Analysis

Fluid analysis is one of the most essential steps in hydraulic systems' maintenance. Results from fluid analysis help determine fluid composition and contamination levels, thus ensuring its adherence to the conditions provided by manufacturers. Visual examination, due to its obvious limits, can never be considered a reliable method for determining fluid conditions. Methodical fluid analysis is the proper way of gaining accurate information on fluid properties.

Fluid analysis usually involves:

- Determining fluid viscosity
- Determining number of particles in the fluid
- Determining the amount of water present in the fluid
- Spectroscopy, analyzing metals and additives content in the fluid

The most important aspect of fluid analysis consists of determining particle count and contamination level of the fluid. This can be done in one of the following ways:

- Based on differential pressure
- Through "Patch Test" using a microscope
- Using portable particle counters
- Through laboratory Analysis

Each of these methods will be discussed below:

Differential Pressure

This is mostly an empirical method which is based on the assumption that when the pressure drop remains constant during a specific period of time, the fluid has reached the required level of cleanliness. This method is very limited and uncontrollable, and thus should only be used as a last resort.

Patch Test

This method consists of passing a fluid sample through a media patch and comparing the remaining particle patterns on the patch against standards such as ISO 4406. A cleanliness indicator is provided as the result of this procedure.

This method is rather time-consuming and requires great experience and precision, while there is a large margin of error.

Particle Counters

Portable particle counters can be used to measure particle numbers and sizes rapidly, conveniently and with great accuracy. The result are usually presented as detailed reports with graphics and tables. Due to their numerous advantages over other counting methods, these devices are increasingly popular.

Figure 26- Particle counters

Laboratory Analysis

Laboratory analysis is the most comprehensive fluid analysis method. Fluid analysis methods usually include identifying the number of particles, fluid viscosity, the water content, and metals and additives existing in the fluid. In addition to these, laboratory analysis also provides analytic charts and graphs, micrography and additional information on the fluid.

A sample report on laboratory analysis is shown on the next page.

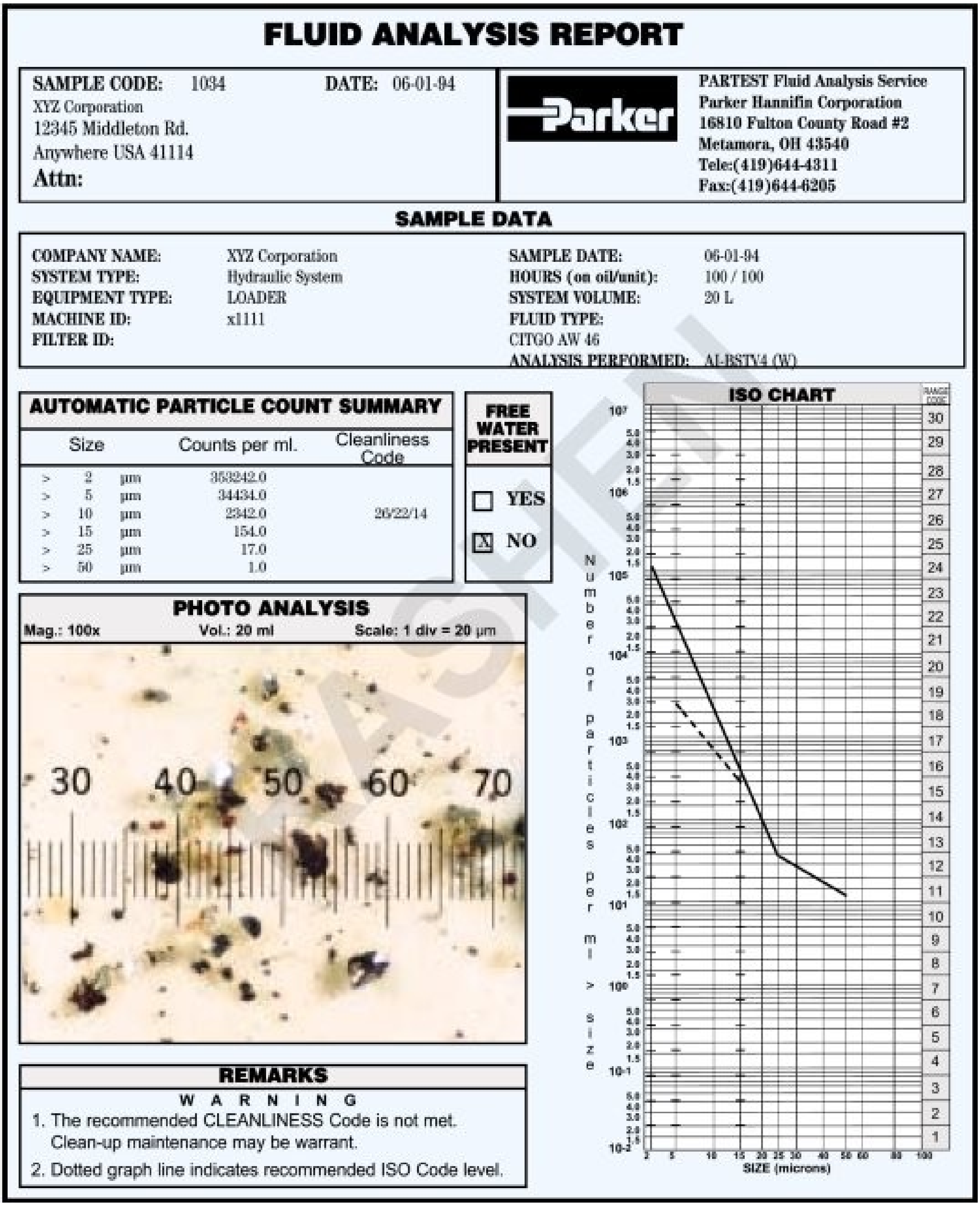

Figure 27- Lab analysis report – image from Parker

Component Cleanliness Levels

In order to reach optimum performance, Hydraulic equipment manufacturers should specify the required fluid cleanliness levels for their products. *Table 6* shows some common hydraulic components and their commonly required ISO 4406 codes.

Component	Required Cleanliness Level (ISO 4406 Code)
Servo Control Valves	17/14/11
Proportional Valves	18/15/12
Vane Pumps and Piston Pumps	19/16/13
Directional and Pressure Control Valves	19/16/13
Gear Pumps	20/17/14
Flow Control Valves and Cylinders	21/18/15
New, unused fluid	21/18/15

Table 6- Required cleanliness levels for hydraulic components

It should be noted, that the specifications and required conditions of hydraulic equipment are provided officially by the manufacturer. In addition to being crucial in determining the required filtration ratio of the system, These specifications are important in keeping the warranty valid by defining the boundary between standard and non-standard use of the system.

Chapter 6 – Filtration and Media

Filtration

The word “filter” means separator: a tool which is used for separating one type of matter from another type. “Filtration” is the act of physically separating different types of matter.

In general, physical separation can be classified into the following types:

- Separation of solids from solids
- Separation of solids from liquids
- Separation of solids from gases
- Separation of liquids from liquids
- Separation of liquids from gases
- Separation of gases from gases

In hydraulics, the possible types of separation are as follows:

- Separation of solids from liquids
- Separation of solids from gases
- Separation of liquids from liquids

Among these, separation of solids from liquids is the most common type in hydraulic systems. The main factor in this type of separation is the filter media, which consists of a structure absorbing undesirable matter from the passing fluid.

Media

Filtration media are responsible for separating contaminants from the fluid. Media are usually produced in the form of sheets, which are sometimes pleated in order to increase their contact area with the passing fluid. This also results in increased filtration ratio and decreased differential pressure. Media can also be employed as multi-layer arrangements.

Filtration media can be made of various materials, including:

- Metal mesh
- Non-metal mesh
- Paper with cellulose fibers
- Paper with micro-fiberglass
- Woven textiles
- Non-woven textiles
- Polymers

There are two main types of filter media: Depth Media and Surface Media.

In surface media, the fluid passes through in a straight path. Surface media usually consists of an interwoven texture with equally sized pores. The diameter of the pores is determined based on the diameter of the largest spherical particle that can pass through the medium in laboratory conditions.

In depth media, the fluid passes through the media layers in a non-straight path. Depth media consists of numerous small pores which are formed by empty spaces between the fibers. These pores create non-straight paths for the fluid to pass. Due to the size distribution of the pores, this type of media is highly capable of absorbing small particles. It is noteworthy that depth media lasts longer than surface media.

Depth media are made of cellulose and fiberglass. In cellulose media, there is a wider variety of pore sizes due to the various types of cellulose fibers. In comparison, fiberglass media consist of thinner fibers with circular profiles, thus having greater performance. Thinner fibers increase dirt-holding capacity by creating smaller pores.

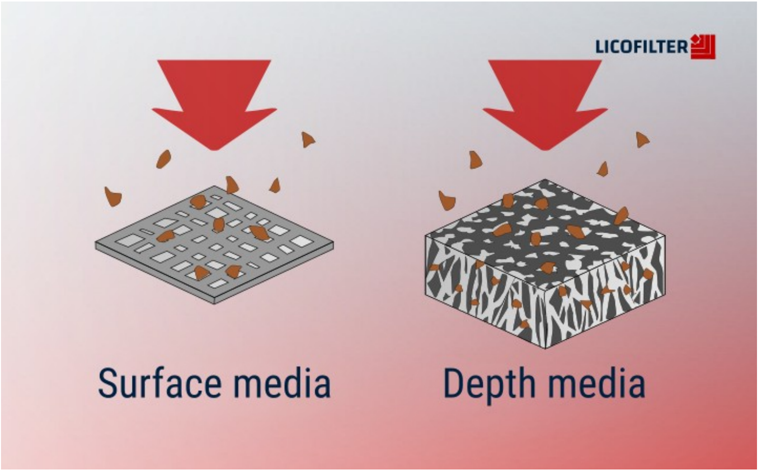

Figure 28- Comparison of surface media and depth media

Filtration Principles

Regarding the separation of contaminant particles from the fluid, there are three main mechanisms in action: Inertial impaction, diffusional interception and direct interception. Based on the size of particles and fluid properties, the effective mechanism would be different. In filtration of hydraulic fluids, oils and fuels, **direct interception** is the main effective mechanism, while inertial impaction and diffusional interception are more effective in air filtration.

Each of these mechanisms are briefly discussed below. The illustrations show the media fibers as perpendicular to the screen. The fluid flows around these fibers.

Inertial Impaction

When particles in the fluid flows towards fibers, the flow changes direction repeatedly to pass through the space between the fibers. However, due to inertia, massive particles such as dust continue to move in the same direction and eventually collide with the fibers.

However, due to the small difference between the density of liquid fluids and the density of the floating particles, the particles diverge only insignificantly from the flow direction. This means that inertial impaction plays a marginal role in the filtration of solid particles from hydraulic fluids.

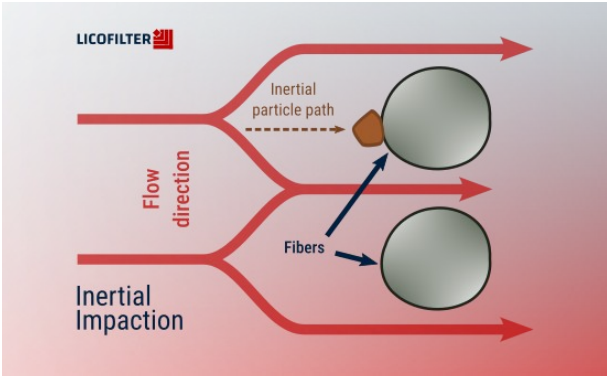

Figure 29- Inertial impaction

Diffusional Interception

In this mechanism, very small particles moving in Brownian motion diverge from the flow path and stop when they collide with fibers.

Since the flow of liquid fluids inherently inhibits random movements and divergences of particles to a great extent, diffusional interception has an insignificant role in hydraulic filtration, similar to inertial impaction.

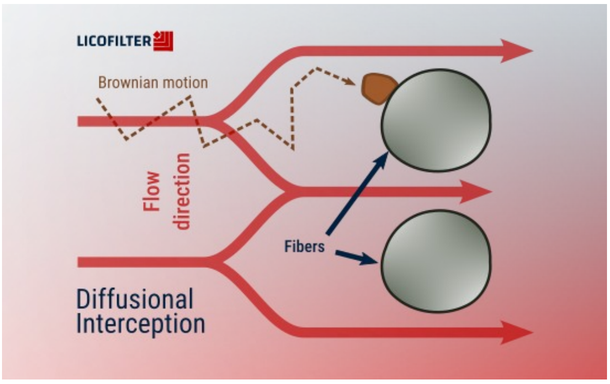

Figure 30- Diffusional interception

Direct Interception

As mentioned before, this is the most common mechanism in action with regard to hydraulic filtration. In direct interception, particles with diameters larger than the pores are stopped easily at the pore entrance. Moreover, usually a great number of small particles are also stopped before entering the media. This can happen due to several causes:

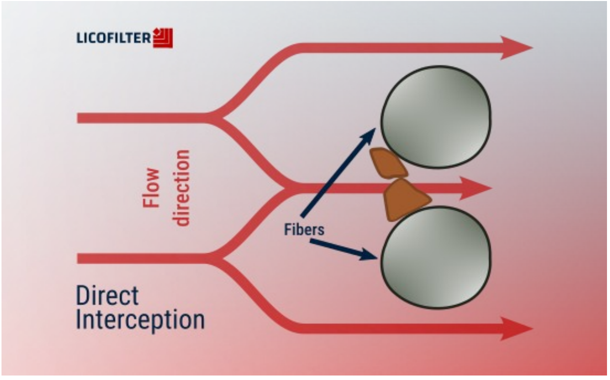

Figure 31- Direct interception

- In reality, particles have irregular shapes Depending on the particle shape and how it sits on the pore entrance, it might stop before entering the media
- When two or more particles collide and stick together at a pore, they cover part of the entrance. This can cause even more particles to be captured and prevent smaller particles from passing through the pore.
- Particles can stick to the inner walls of pores due to the physical interactions between them. Such interactions can be caused by opposite electrical charges of the two surfaces.

Element Life

Over time, contaminants accumulate on the surface of the medium and start to clog the pores. Over time and with more use, the contaminant layer becomes thicker and limits the capacity of the pores. This, in turn, increases the differential pressure.

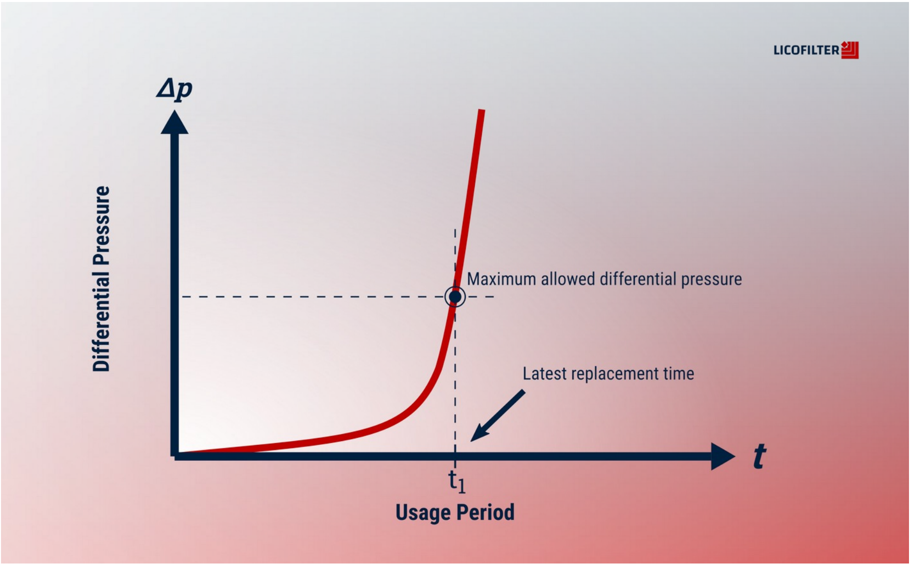

Figure 32- Differential pressure over time

Figure 32 illustrates the relationship between the differential pressure (Δp) and duration of use (or level of contamination). Although the differential pressure increases slowly, when the dirt-holding capacity is surpassed, the differential pressure reaches the critical point quickly, which means the element has to be replaced.

The time point t_1 should be provided in the component's specifications. Each element has a specific differential pressure. Differential pressure is related to the amount of contaminant held in by the element and also to factors such as the flow rate and fluid viscosity. This relationship can be depicted as the "element life curve".

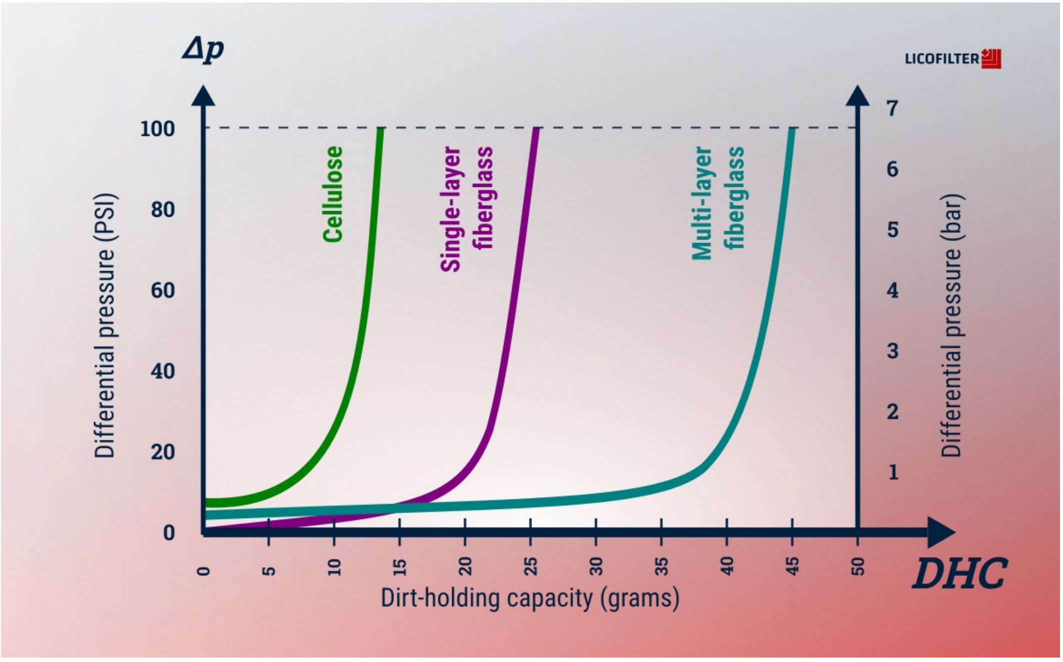

Figure 33- Element life defined as dirt-holding capacity (DHC) by filtration medium

Figure 33 shows element life curves for three different media. The graph shows how the material used in the media can affect element life. Elements using fiberglass media provide better dirt-holding capacity compared to those made of cellulose, due to the structure of these media.

Chapter 7 – Efficiency and Beta Ratio

Filtration efficiency of an element indicates its capability in separating contaminant particles with specific sizes from the fluid. The prior step to determining the efficiency is determining an indicator called the “Beta Ratio”, also known as the “Filtration Ratio”.

The Beta Ratio (β_x) for particles of a specific size range (x) consists of the ratio of the number of particles in the upstream flow to the number of particles in the downstream flow. This ratio is used in the filtration industry as a factor of element efficiency. However, it is not adequate for understanding an element’s performance.

Determine the Beta Ratio for an element is done based on a method known as the Multi-pass test, which is described in the ISO 16889 standard.

Multi-pass Test

In this method, a certain amount of solid particles with certain size is continuously introduced into a slowly flowing fluid passing through a filter in controlled lab conditions. Through the test, the contamination levels of the fluid are measured before and after passing through the filter, using particle counters.

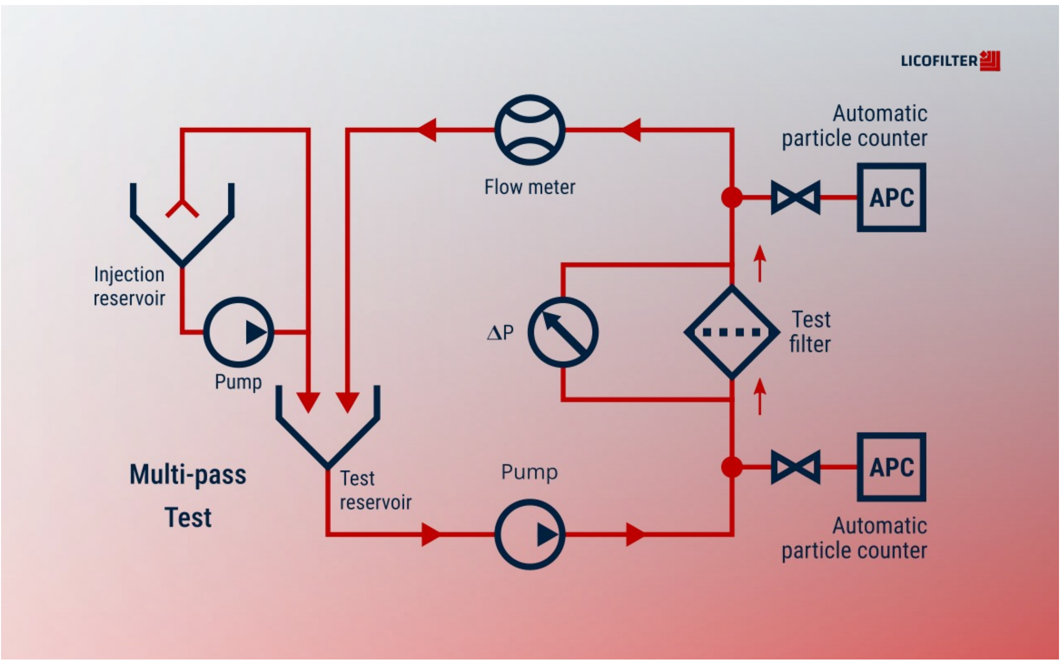

Figure 34- Multi-pass test

Based on these measurements, several indicators are determined for a filter element, including the Beta ratio for particles with certain sizes.

Results of a Multi-pass test determine three major factors of element performance:

- Dirt-holding Capacity
- Differential Pressure
- The filtration Ratio, which is known as the “Beta Ratio”

Determining the Beta Ratio

An element's Beta Ratio is calculated using the following formula:

$$\beta_{(x)} = \frac{N_{u(x)}}{N_{d(x)}}$$

where:

- $\boldsymbol{\beta_{(x)}}$ is the filtration ratio for particles of x µm and larger
- $\boldsymbol{N_{u(x)}}$ is the number of particles of x µm and larger present in the *upstream flow*
- $\boldsymbol{N_{d(x)}}$ is the number of particles of x µm and larger present in the *downstream flow*

Therefore, the filtration ratio (the Beta Ratio) is calculated by dividing the number of upstream particles by the number of downstream particles. For example, if the beta ratio of a filter element is expressed as $\beta_{10} = 200$, it can be concluded that there are 200 times more upstream particles of 10µm in diameter (and larger) than downstream particles in the same size range. In other words, the element is capable of reducing the number of particles of 10µm and larger in diameter to 1/200 in the fluid stream. Figure 35 on the next page illustrates this example.

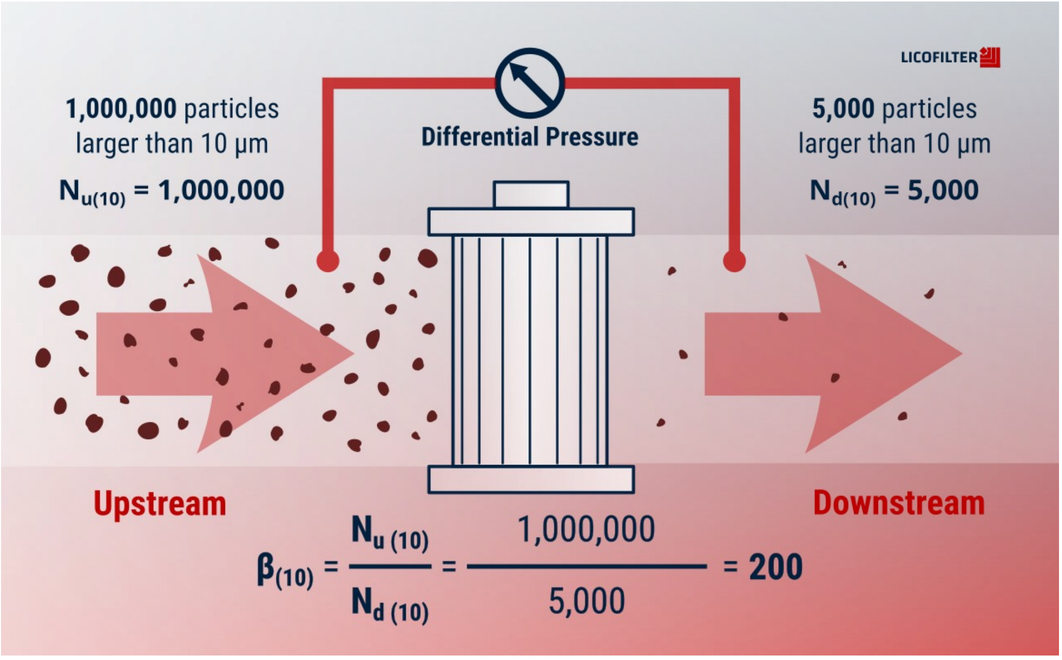

Figure 35- Determining Beta Ratio based on upstream and downstream flow

Calculating Element Efficiency

The following formula uses the Beta Ratio as the basis to calculate the filtration efficiency of an element in percentage form:

$$E_{(x)} = \left(1 - \frac{1}{\beta_{(x)}}\right) \times 100$$

where:

- $E_{(x)}$: The filtration efficiency of the element for particles of *x* µm *and larger*
- $\beta_{(x)}$: Filtration ratio of the element for particles of *x* µm and larger

For example, the filtration efficiency for particles of 10µm and larger in an element with a Beta Ratio of 200 in the same size range would be calculated as follows:

$$E_{(10)} = \left(1 - \frac{1}{\beta_{(10)}}\right) \times 100 \quad = \left(1 - \frac{1}{200}\right) \times 100 \quad = 99.5$$

The result is expressed as 99.5%.

Relation between Efficiency and Beta Ratio

Table 7 shows the relationship between the Beta Ratio and efficiency in percent form.

Filtration Ratio (β) **for particles in a specific size range**	**Filtration Efficiency** **for particles in the same size range**
2	50%
5	80%
10	90%
20	95%
75	98.7%
100	99%
200	99.5%
1000	99.9%

Table 7- Common Beta Ratios and their corresponding efficiencies

It can be seen in the table, that there is a 0.4% difference between the efficiencies 99.5% and 99.9%, while the difference between the corresponding beta ratios (200 and 1,000) is 800. Therefore, a Beta Ratio difference is more obvious than an efficiency difference.

Although the most important role of the beta ratio is as a parameter in calculating the filtration efficiency, the parameter itself is also effective in understanding the expected separation capacity and efficiency.

Chapter 8 – Filter Locations in a Hydraulic Circuit

Every hydraulic circuit consists of various types of pumps, motors, valves, cylinders, reservoirs, filters and bypasses. Based on their roles and locations, filters used in hydraulic circuits can be categorized into **suction filters**, **pressure line filters**, **return line filters** or **off-line filters**.

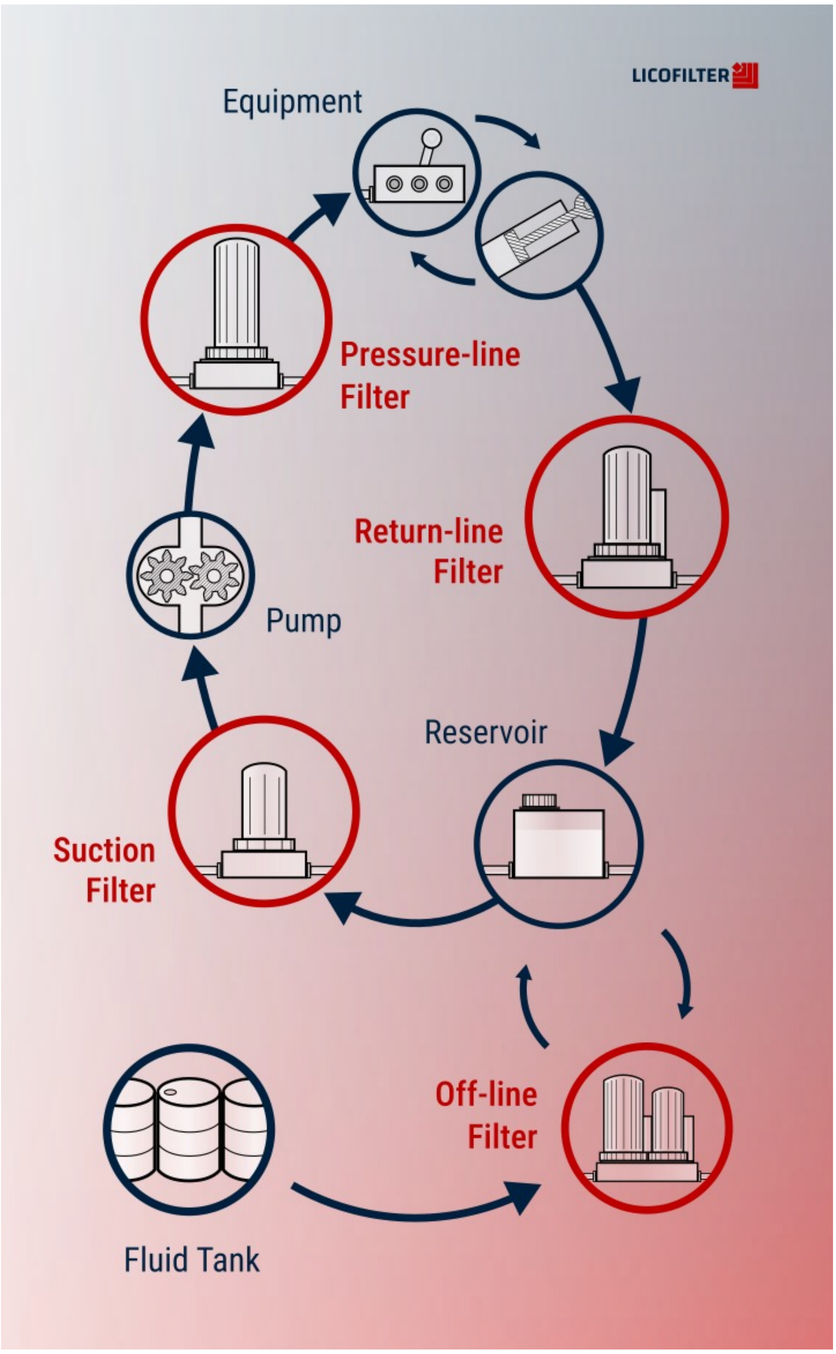

Figure 36- Filter locations in a hydraulic circuit

Figure 36 shows a circuit containing all filter types. Each is discussed below.

Suction Filters

Suction filters are responsible for protecting the pump against contaminants in the fluid and are located before the pump inlet. In order to prevent cavitation in pumps, these filters use elements with relatively low filtration ratios. This means suction filters cannot be used as the main protective measure, and therefore they are not usually recommended by manufacturers of pumps and hydraulic components.

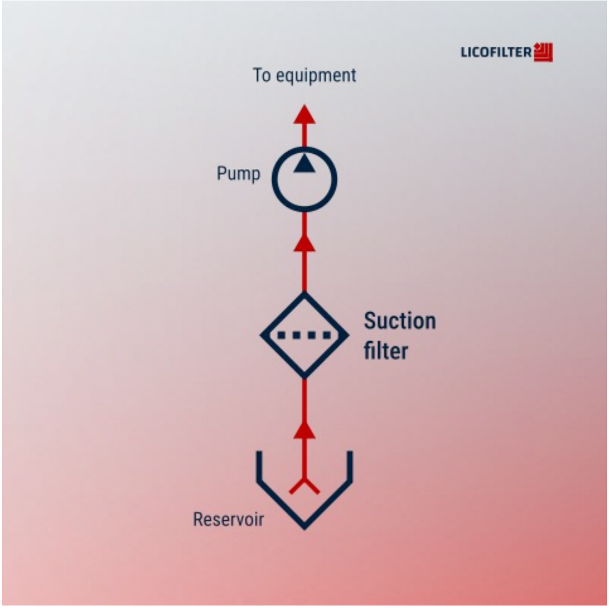

Figure 37- Suction filter in a hydraulic circuit

Pressure Line Filters

Pressure line filters are installed close to the pump on the downstream flow. These filters are designed to endure system pressure, and their size is determined based on the flow rate in the line on which they are installed.

Due to their location on the circuit, pressure line filters are usually responsible for protecting the equipment located just after the pump. These filters also protect the entire system from the contamination originating from the pump.

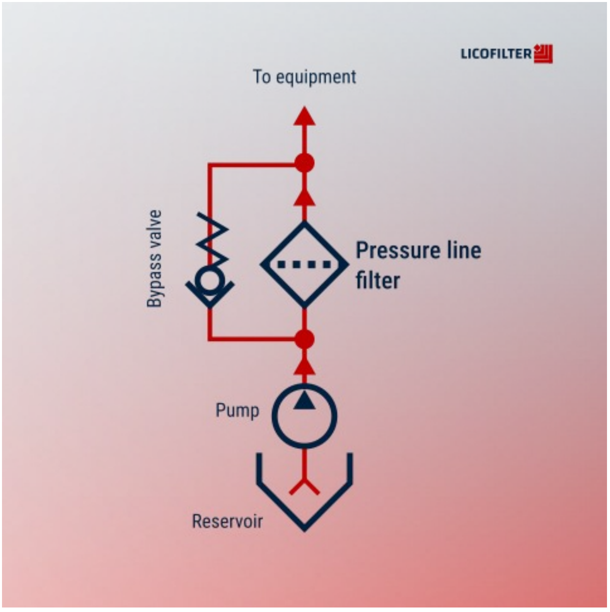

Figure 38- Pressure line filter with bypass route

It should be noted, that these kinds of filters need to be capable of enduring the highest pressure possible in the system and require a high filtration ratio. Moreover, based on the filtration levels required by other equipment in the circuit, installing other filters on the circuit might be necessary.

Return Line Filters

Return line filters are the best choice for the situations where the pump is considered a critical or sensitive part of the system. In most systems, these filters are the last part which the fluid enters before re-entering the reservoir. This positioning removes particles created by component wear and particles that have entered the circuit from the fluid before the fluid re-enters the reservoir.

Since return line filters are located just before the reservoir, they are usually exposed to less pressure and are associated with lower costs compared to pressure line filters.

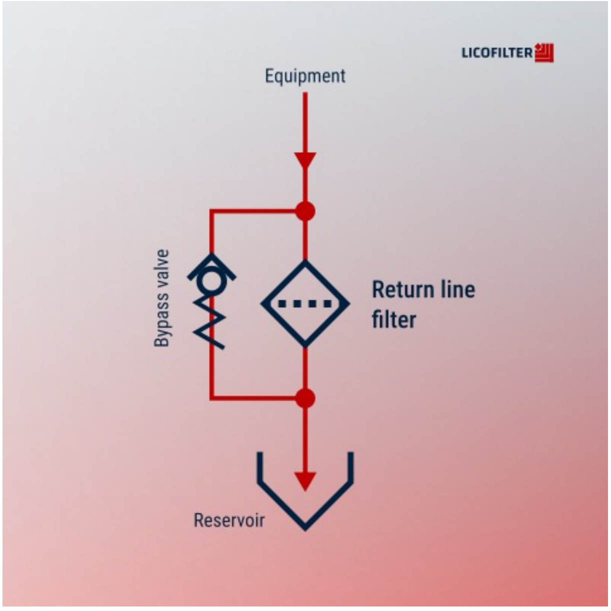

Figure 39- Return line filter with bypass route

Off-line Filters

Off-line filters, also known as auxiliary filters, are located in their own "kidney loop" circuits and function completely independent of the main circuit.

This auxiliary loop contains a separate pump, filter, motor and other necessary parts, and is installed as a smaller sub-system to the main circuit. The fluid which is constantly pumped out of the reservoir passes through the offline circuit and eventually goes back in the reservoir. Use of offline filters can help keep fluid contamination at a constant level.

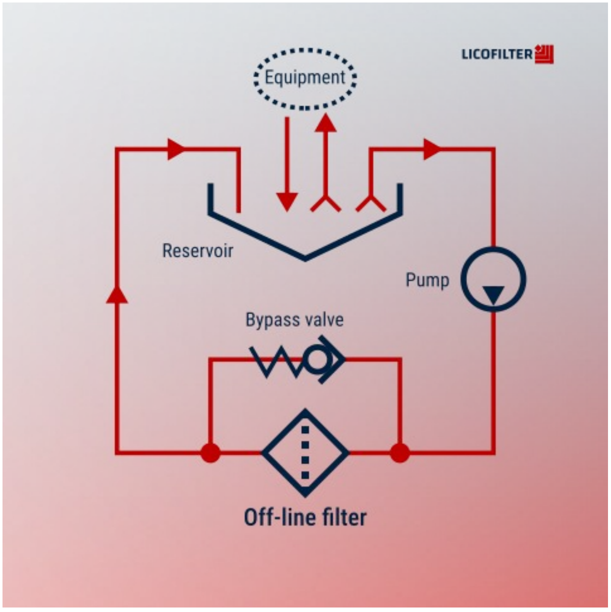

Figure 40- Off-line filter with bypass route

Duplex Assembly

Pressure line and return line filters can also be installed as duplex assemblies. In a duplex assembly, filters with the same efficiencies are installed in parallel. This has several advantages, including:

When one of the filters is clogged (reached its DHC limit), the fluid can pass the other filter, thus delaying a bypass (which will be discussed later).

When one of the filters is in need of maintenance or replacement, the system can function continuously while the necessary operations are done.

Figures 41 and 42 show the duplex assemblies of pressure line and return line filters.

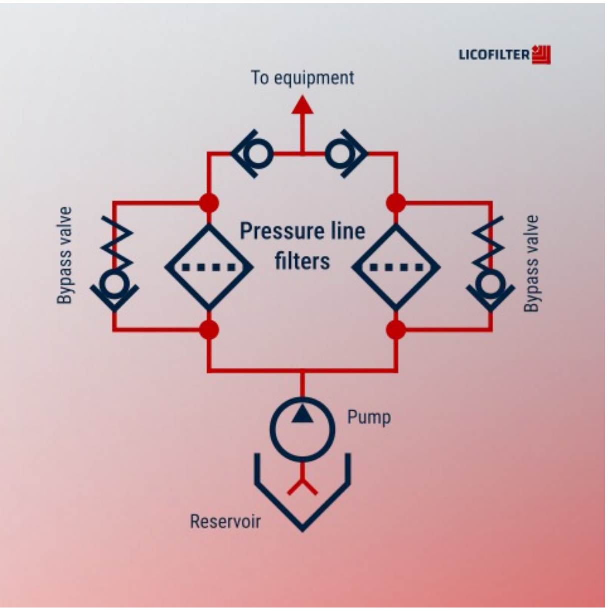

Figure 41- Duplex assembly of pressure line filters

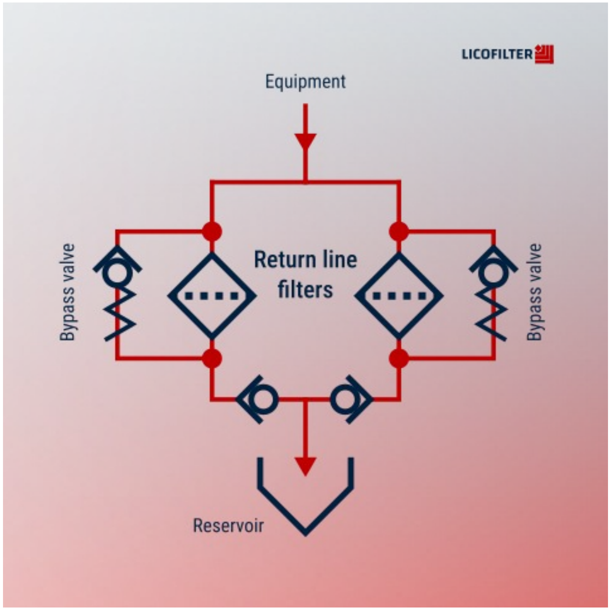

Figure 42- Duplex assembly of return line filters

Bypass Route

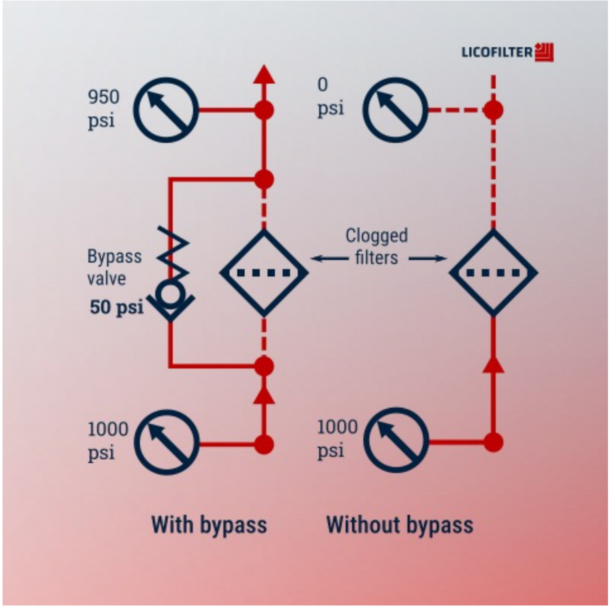

Figure 43- Bypass route in a hydraulic circuit

In fluids-related systems such as hydraulic or lubricating circuits, irrigation and gas supply systems, the most crucial principle is that the fluid must reach the components. Clogging or other problems can cause filters used in these systems to stop working. In that case, the fluid will not be able to pass through the element. This is indicated by increased differential pressure between upstream and downstream to a higher level than the specified limit. There are two possible choices in such a situation: either let the flow stop, or provide a temporary alternate route for the fluid.

The former means the flow is completely stopped and components halt until the element is replaced. In contrast, the latter means the unfiltered flow is still constantly reaching the components and keeps them functional until the element is replaced.

The choice depends on the type and conditions of the system and equipment. While the unfiltered fluid can cause damage to the system, a sudden stop of the flow might also involve risks and hazards. Therefore, the need of a bypass system should be taken into account when designing a hydraulic system. For example, in lubricating equipment, it is much more crucial that the fluid, even unfiltered, is supplied to the equipment. Similarly, for hydraulic jacks and lifts under load and working, a system halt due to a flow stop can result in damage and safety hazards.

In a situation where the flow stop might cause disruptions in the system, the main route is temporarily blocked and the fluid is directed into an alternate route until the element is replaced. This is called a “bypass route” and is often activated using a “bypass valve”. A bypass valve automatically redirects the flow into the bypass route when there is clogging or excessive differential pressure in the flow. The valve can be installed as a separate unit, on the filter housing, or inside it.

In Figure 43 the right circuit lacks a bypass system, so the flow will stop in case of exceeding differential pressure. As a result, the fluid will no longer reach components, causing them to halt. In contrast, the left circuit will have constant flow thanks to the bypass system. As long as the element is not replaced, the fluid will not pass the filter and therefore will lack proper filtration. In both situations, it is not adequate to use pressure indicators. In order to prevent damage, it is advisable that an alarm system be employed so that the operator can be notified of exceeding differential pressure as early as possible.

Chapter 9 – Determining Filter Placements for a Circuit

In hydraulic systems, filtration is considered as a crucial issue in increasing system efficiency and life expectancy. To achieve this, types and numbers of filters in a hydraulic circuit must be selected and determined with great care. The goal of what discussed in all the previous chapters is to provide a better understanding of filtration and proper selection of filters.

To decide the optimum number and the right types of filters for a given circuit, there are several factors to be considered. Special software can be used to reach an optimum combination. However, general rules based on empirical data are often used as a starting point for this decision-making process.

Two deciding factors for determining filter placements are the allowed size of particles present in the system and the minimum size of particles that are to be separated from the fluid. This is crucial in deciding the element pore size and efficiency. The size and number of particles determine the "cleanliness" level of the fluid. The required cleanliness levels for different hydraulic components have been discussed earlier under "Fluid Analysis". Efficiency has also been discussed under "Efficiency and Beta Ratio".

The most important factors for choosing filters in a hydraulic circuit include:

- System pressure and its fluctuations
- Work conditions
- Component sensitivity levels
- Component life expectancy
- Filter life expectancy
- Equipment maintenance and replacement costs
- Gravity of uninterrupted operation
- Allowed flow rate and pressure drop
- Safety costs

Table 8 on the next page can be used as a guide for determining types and placements of hydraulic filters in a circuit. The data shown in the table are provided for a Beta ratio of greater than 200 and is calculated based on empirical data. The table shows data for hydraulic equipment with varying degrees of sensitivity, sorted from more sensitive to less sensitive.

It is advisable to pay attention to the following while using the table:

- Each "Placement" can include a single or duplex filter installation.
- A slash (/) indicates that only one of either type is needed. Further placements must be based on expert advice.
- **P** indicates a Pressure-line filter (1 placement)
- **R** indicates a Return-line filter (1 placement)
- **O** indicates an Off-line filter (0.5 placement, for a flow rate of 10% of reservoir volume per minute)*

** The number of Off-line filters placements is calculated as follows:*

$$N_O = \frac{\left(\frac{Q}{2}\right)}{\left(\frac{V}{10}\right)}$$

Where:

- N_O: The number of Off-line filter placements
- Q: The flow rate of the fluid (per minute) and
- V: The reservoir volume.

Equipment	System pressure (PSI)	Recommended cleanliness level (ISO 4406)	Pore size (x) (µm)	Minimum number of "placements"	Filter types required in circuit
Servo valves	< 1000	17/14/12	2	1	P
			5	2	P + R
	1000 – 3000	16/13/11	2	1.5	P + O
	> 3000	16/12/10	2	2	P + R
Proportional Valves	< 1000	18/15/13	2	1	P
			5	1.5	P + O
			10	2.5	P + R + O
	1000 – 3000	18/14/12	2	1	P
			5	2	P + R
	> 3000	17/14/11	2	1.5	P + O
			5	2.5	P + R + O
Variable displacement pumps	< 1000	19/16/14	5	1	P/R
			10	2	P+R
	1000 – 3000	18/16/14	2	0.5	O
			5	1.5	P/R + O
			10	2.5	P + R + O
	> 3000	18/15/13	2	1	P/R
			5	2	P + R
Vane Pumps, Fixed Piston Pumps, Cartridge Valves	< 1000	20/17/15	5	0.5	O
			10	1.5	P/R + O
	1000 – 3000	19/17/14	5	1	P/R
			10	2	P + R
	> 3000	19/16/13	5	1.5	P/R + O
			10	2.5	P + R + O
Gear Pumps, Flow meters, Cylinders	< 1000	21/18/16	10	1	P/R
			20	2.5	P + R + O
	1000 – 3000	20/17/15	10	1.5	P/R + O
	> 3000	20/17/14	5	0.5	O
			10	1.5	P / R + O

Table 8- Determining type and placement numbers of filters in a hydraulic circuit for an efficiency of $\beta > 200$

The same method is used for lubrication circuits, as shown in *Table 9* below:

Equipment	Recommended cleanliness level (ISO 4406)	Pore size (x) (µm)	Minimum number of "placements"	Filter types required in circuit
Ball-bearings	16/13/11	2	1.5	P/R + O
		2	1	P/R
Roller Bearings	17/14/12	5	2	P + R
		2	0.5	O
Plain Bearings, Gearboxes	18/15/13	5	1.5	P/R + O
		10	2.5	P + R + O

Table 9- Determining type and placement numbers of filters in a lubrication circuit for an efficiency of $\beta > 200$

Media Selection

Since hydraulic filters are designed to endure the common high workload in hydraulic systems, the filtration media used for these filters is usually made of reinforced micro-fiberglass.

To determine the required pore size for a filter in a given circuit, it is common to use the method described on the following pages, which is based on choosing a weighting factor for each of the 7 predefined system parameters and finally adding them.

- Workload and System Pressure
- Work Conditions
- Equipment Sensitivity
- Life Expectancy
- Replacement Costs
- Downtime Costs
- Safety Costs

Using the System Factor Tables

Each factor is extracted from the corresponding table. These tables are shown below along with examples for each score:

1. Pressure and Workload Levels

Pressure		Workload			
PSI	BAR	Light	Medium	Heavy	Severe
0 – 1050	0 – 70	1	2	3	4
1050 – 2175	70 – 150	1	3	4	5
2175 – 3625	150 – 250	2	3	4	6
3625 – 5075	250 – 350	3	5	6	7
5075 +	350 +	4	6	7	8

Table 10- Weighting factors for levels of system pressure and workload

Workload levels are defined as follows:

- **Light:** Constant operation at the pressure limit or lower
- **Medium:** Mild changes in pressure up to the limit
- **Heavy:** Zero to maximum pressure
- **Severe:** Zero to maximum pressure — with frequent fluctuations

2. Work Environment

Work Conditions	Weighting Factor
Desirable	0
Acceptable	1
Undesirable	2
Harsh	3

Table 11- Weighting factors for different work environments

Here are some examples for each work condition:

- **Desirable:** Clean environments, laboratories
- **Acceptable:** Machinery workshops, assembly workshops
- **Undesirable:** Construction sites, outdoor work environments, places where milling machines are used
- **Harsh:** Metal casting and smelting workshops, any environment where contaminant ingression rates are expected to be high.

3. Equipment Sensitivity

Sensitivity	Weighting Factor
Very High	8
High	6
Above Average	4
Medium	3
Below Average	2
Minimal	1

Table 12- Weighting factors for different levels of equipment sensitivity

Here are examples for each sensitivity level:

- **Very High:** High precision servo valves
- **High:** Industrial servo valves
- **Above Average:** Piston pumps, proportional valves, pressure-compensated flow control valves
- **Average:** Vane pumps and spool valves
- **Below Average:** Gear pumps, foot valves, manual valves
- **Minimal:** Ram pumps and cylinders

4. Equipment Life Expectancy

Life Expectancy (hours)	Weighting Factor
0 – 1,000	0
1,000 – 5,000	1
5,000 – 10,000	2
10,000 – 20,000	3
20,000+	5

Table 13- Weighting factors by life expectancy of different equipment

5. Equipment Replacement Costs

Cost Level	Weighting Factor
Very High	4
High	3
Medium	2
Low	1

Table 14- Weighting factors for replacement costs for different equipment

Examples for levels of replacement costs:

- **Very High:** Large piston pumps, large motors with high torque and low velocity
- **High:** Cylinders, servo valves, piston pumps
- **Medium:** Valves on the circuit
- **Low:** Sub-plate valves, inexpensive gear pumps

6. Downtime Costs

Cost Level	Weighting Factor
Very High	5
High	3
Medium	2
Low	1

Table 15- Weighting factors for downtime costs of different systems

Example equipment types for each level of downtime costs:

- **Very High:** Some milling machines and mobile equipment
- **High:** Mass production equipment
- **Medium:** Non-production related, yet critical equipment
- **Low:** Non-critical equipment

7. Safety Costs

Cost Level	Weighting Factor
High	3
Medium	1
Low	0

Table 16- Weighting factors for safety costs of different systems

Example equipment types for each level of safety costs:

- **High:** Large rotating equipment, e.g. mining and excavation equipment
- **Medium:** Equipment where any failure or interruption could cause safety hazards
- **Low:** Laboratory equipment

After specifying a weighting factor for each of the seven factors and calculating their total, the minimum and maximum pore sizes for the situation can be found from the table below:

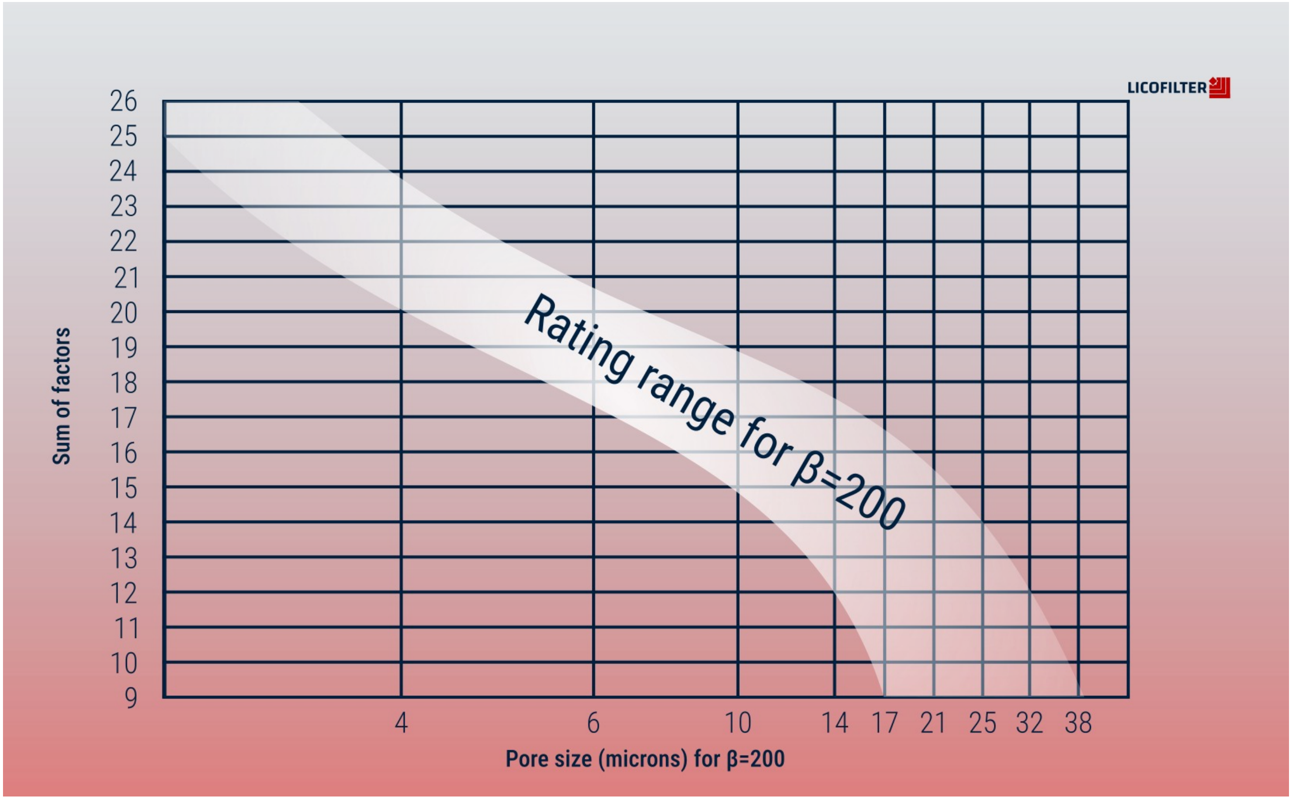

Figure 44- How to select medium pore size based on system factors and β=200

For a better understanding, see the following example:

Example

Scenario:

Let's imagine a hydraulic excavator working in a silica mine. The machine is equipped with pressure-compensated piston pumps and large lifting cylinders.

System Parameters:

Based on these conditions, the seven system parameters are determined as follows:

1. Pressure and Workload Levels (Table 10)

The example system operates at 2500 psi and reaches maximum and minimum flows and pressures in cycles that repeat approximately three times in a minute. This puts the workload levels in the "Heavy" category.

*Weighting factor from the table: **4***

2. Work Environment (Table 11)

The working environment of the machine includes a considerable amount of silica particles. Due to the size of these particles, the environment is classified as "Harsh"

*Weighting factor from the table: **3***

3. Equipment Sensitivity (Table 12)

Due to the relatively high sensitivity of the pumps used in the machine, the system is considered to be of "Above average" sensitivity.

*Weighting factor from the table: **4***

4. Life Expectancy (Table 13)

Taking into account the 3,600 hours of average annual work hours and 5 years of life expectancy for the system, the expected lifespan would be 18,000 hours, falling in the 10,000~20,000 range.

*Weighting factor from the table: **3***

5. Replacement Costs (Table 14)

Since equipment such as lifting cylinders and piston pumps are of relatively high cost, the replacement costs are considered “High”.

Weighting factor from the table: ***3***

6. Downtime Costs (Table 15)

The downtime costs may vary based on the environment conditions. Despite the high capital costs of the system, usually two or more excavators are employed at the same time in silica mines, therefore the downtime costs for this system are considered “Medium”

Weighting factor from the table: ***2***

7. Safety Costs (Table 16)

Considering that the operation involving the heavy machinery takes place in open-air sites while human work is mostly done indoors, safety costs is considered to be “Medium” for this system.

Weighting factor from the table: ***1***

Total

The sum of the factors for the system is **20**. Putting the numbers in the table illustrated in Figure 44, the maximum and minimum media pore diameters for the system are found to be between 4 and 7 microns, based on the results, as shown in Figure 45 on the next page.

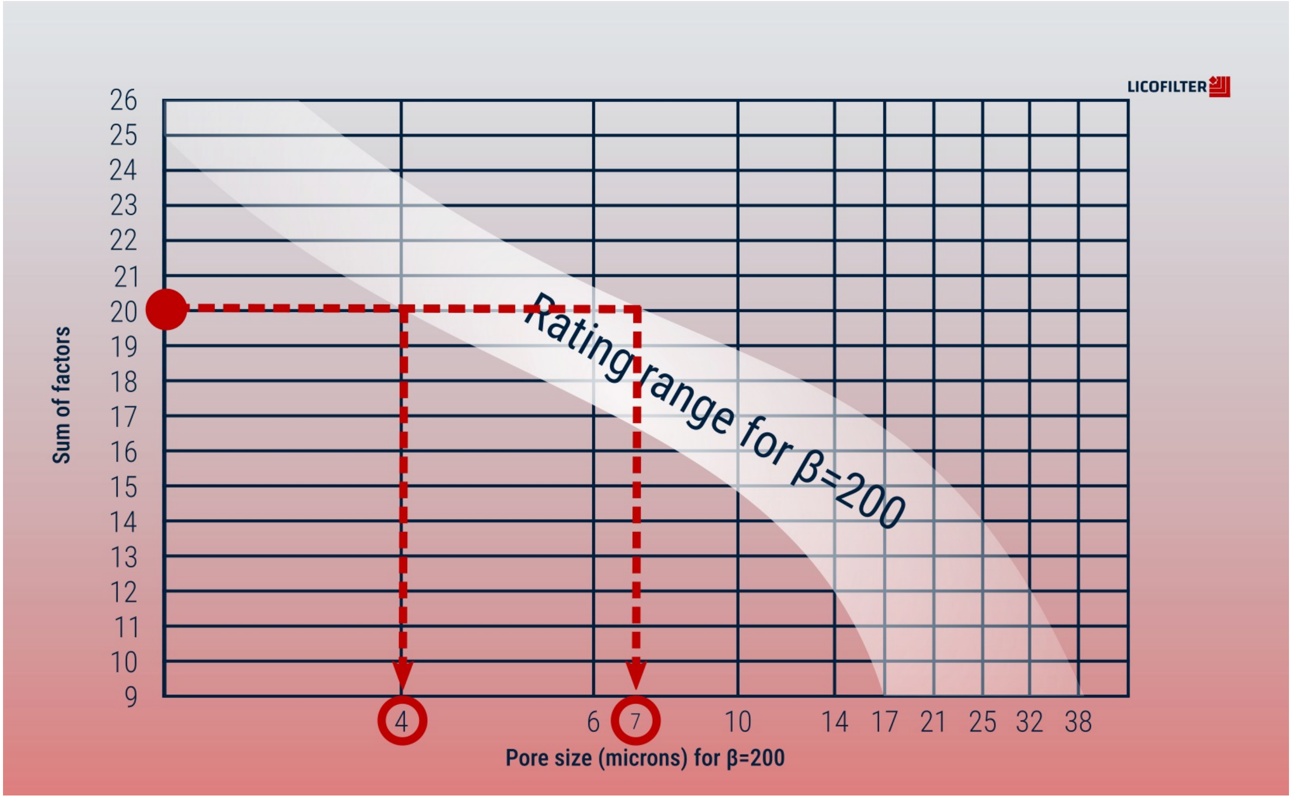

Figure 45- Pore size selection based on system factors for the example (for β=200)

It should be noted that the table is designed for elements with an efficiency of β=200, which is very common for hydraulic filters. In our example, proper filtration media for the described conditions must have a filtration ratio of β_7=200, or in other words, an efficiency of 99.5%[1].

It is important to note, that the methods mentioned should be used only as auxiliary methods, and that the final decisions should be based on expert advice.

1 To see how to calculate efficiency based on beta ratio, refer to the chapter “Efficiency and Beta Ratio”

Housing Selection

Housing selection and design is based on filter locations and system conditions, Including:

- Need for bypass valves
- Need for a drain port
- System pressure at the filter location
- Need for monitoring equipment, such as pressure gauges
- Physical properties of the fluid
- Chemical properties of the fluid

Based on these requirements, a housing can be designed either as a fixed part of a system, with the element being replaceable, or as a unit including the element. In the latter case, the housing and the element could not be replaced separately.

Figure 46 shows the section of a filter housing that includes a bypass valve, a drain valve and upstream and downstream pressure indicators.

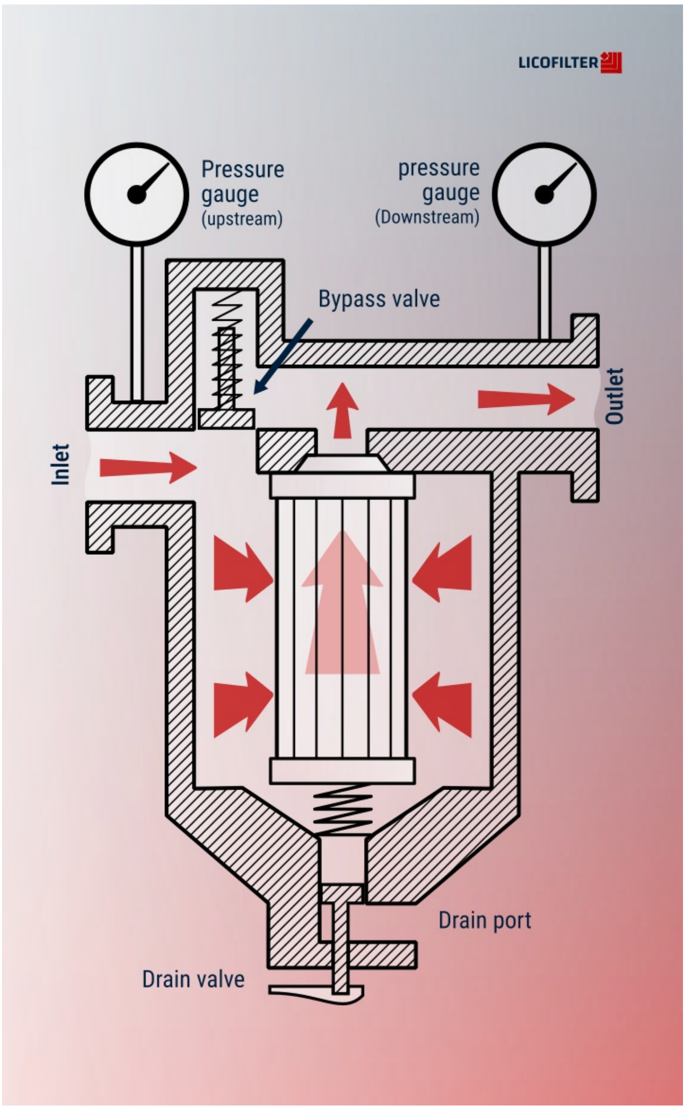

Figure 46- Section of a housing with bypass valve, drain valve, pressure indicators and the filter element

Bibliography

- Madani, Hassan. **Fluid Mechanics and Hydraulics**. Jahad Daneshgahi Publications. Tehran 1993.
- **Standard No. 2525 – Engine Oil Filters: Properties and Testing Methodology**. Institute of Standards and Industrial Research of Iran.
- **Standard No. 4201 – Performance Evaluation Test for Hydraulic Filters (Repeat Method)**. Institute of Standards and Industrial Research of Iran.
- Pall Corporation. **Principles of Filtration**. https://www.pall.fr/pdfs/Fuels-and-Chemicals/WER_5300B.pdf
- Pall Corporation. **Filtration E-Book**. https://www.pall.com/content/dam/pall/industrial-manufacturing/literature-library/non-gated/M&EPOCKETENf.pdf
- Parker Corporation. **Handbook of Hydraulic Filtration**. https://www.parker.com/literature/Hydraulic%20Filter%20Division%20Europe/fdhb289uk.pdf
- Hydac International. **Filter Handbook**. https://m.hydac.com/fileadmin/pdb/pdf/PRO000000000000000000007011040011.pdf

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For designers, manufacturers and users of hydraulic systems, it is important to be aware of the properties of hydraulic fluids, their contaminants and the common damages caused by contaminants to hydraulic equipment. These factors are crucial in effective design and use of filtration systems.

This handbook aims to serve as a general guide on hydraulic filtration systems, especially for persons with limited expertise on the subject.

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