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Hydraulic fluid power contamination control — General principles and guidelines for selection and application of hydraulic filters

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National foreword

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Hydraulic fluid power contamination control — General principles and guidelines for selection and application of hydraulic filters

Vérification de la contamination des transmissions hydrauliques — Principes généraux et lignes directrices pour l'application et la sélection des filtres hydrauliques

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Foreword

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In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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ISO/TR 15640 was prepared by Technical Committee ISO/TC 131, *Fluid power systems*, Subcommittee SC 6, *Contamination control*.

Introduction

Hydraulic systems transmit power by means of a pressurized liquid in a closed circuit. Foreign materials or contaminants present in the fluid can circulate around the system, cause damage to the component surfaces, and reduce the efficiency, reliability and useful life of the system. Hydraulic filters are provided to control the number of particles circulating within the system to a level that is commensurate with the degree of sensitivity of the components to the contaminant, and the reliability and durability objectives of the hydraulic system.

The selection and application of filters takes into account the filter design and performance, the system design and function, the required cleanliness level (RCL), the severity of the system operation and the standard of maintenance. The only way to confirm whether the correct filter has been selected is to monitor the cleanliness level in the fluid, and the reliability and durability of the system.

These guidelines are intended to introduce the concepts of cleanliness management and filter selection and application to both system designers and users. Although this guide cannot make one an expert on filter selection and use, it does seek to educate and thereby assist the reader in making informed decisions about filtration, and to improve the communication process.

Hydraulic fluid power contamination control — General principles and guidelines for selection and application of hydraulic filters

1 Scope

This Technical Report is applicable to contamination control principles for hydraulic fluid power systems and includes guidelines for the selection and application of hydraulic filters. Although control of non-particulate contamination, e.g. air, water and chemicals, is important, and is briefly discussed, the primary focus of this Technical Report is the control of particulate contamination and the selection and application of filters for that function.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 5598, *Fluid power systems and components — Vocabulary*

NOTE The other documents mentioned and referenced in this document in a non-normative way are listed in the Bibliography.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 5598 and the following apply.

3.1
contaminant
any material or combination of materials (solid, liquid or gaseous) that can adversely affect the system

3.2
ingression
introduction of environmental contamination into the system

NOTE Contamination introduced through ingression is referred to as ingressed contamination.

3.3
filter medium
part of the filter structure that removes and retains contaminant

3.4
filter media
collective layers that make up a filter element

4 Types and sources of contamination

4.1 General

Contaminants in a hydraulic fluid are any material or combination of materials (solid, liquid or gaseous) that can adversely affect the system.

4.2 Solid contaminants

4.2.1 General

Solid contaminant particles come from four main sources as shown in Table 1 and can vary considerably in material, hardness, shape and size from sub-micrometre to millimetres.

Contaminant shape varies widely and debris can appear as granular (cube-shaped), acicular (rod-shaped), platelets (very thin, nearly two dimensional), irregular fragments and fibres. Shape affects the way that particles are aligned in the moving fluid and thus the likelihood of the particles becoming lodged in a small clearance or trapped within the filter medium. Although quite important, particle shape is rarely reported because of the difficulties involved in its determination.

Table 1 — Primary sources of particulate contamination

Built-in (manufacturing debris)	Ingressed		Generated		Maintenance (service debris)
	Process	Atmosphere	Surfaces	Fluid	
– burrs – machining swarf – weld spatter – abrasives – drill turnings – filings – dust – contaminated components – dust from grinding – incompatible fluids – paint chips	– initial fluid fill – addition of incorrect fluid – compressed air or gas – pulp – pulverized coal – ore dust – aggregates – cement – catalysts – clays – process chemicals	– ingestion via reservoir breather – ingestion via seals – reservoir opening – rock dust – mill scale – quarry dust – foundry dust – slag particles – dust from welding and grinding	– mechanical wear – corrosive wear – cavitation – exfoliation – hose materials – filter fibres – break-in debris – elastomers	– re-entrainment – filter desorption – additive precipitation – sludge – insoluble oxides – carbonisation – coke – aeration – varnishes	– repairs – preventive maintenance – new filter – new fluid – dirty hose, connector, components – top-up containers – incorrect fluid – cleaning rags – dust from welding and grinding – dust from atmosphere and workplace

4.2.2 Built-in contaminant

All new systems contain some contaminant left during manufacture and assembly. This can consist of fibres (from rags, etc.), casting sand, pipe scale, cast iron or other metal particles, jointing material or loose paint. When a system is operated at an unusual load or if there are high pulsations in the flow, it is likely that built-in contaminant becomes dislodged.

4.2.3 Ingressed contaminant

Systems can also be contaminated during normal operation, through openings in the reservoir, inadequate air breather filters, through worn seals in vacuum conditions and by intrusion through the fluid film on piston rods. Worn seals increase the likelihood of ingression. These ingressed contaminants can be highly abrasive.

4.2.4 Generated contaminant

When a normal system has been run for a reasonable period of time, a quantity of solid contaminant can be present in the form of small metallic platelets, created by the normal wear process. For correctly designed systems, which are provided with suitable filtration, the majority of these particles are smaller than 15 µm. If a filter blockage indicator is ignored, previously retained contaminant can be dislodged from the filter element (see 10.4.1). However, if abnormal wear occurs, both the size and quantity of particles increase and, if not detected by monitoring, wear rates can accelerate and the wear mode can change from benign fatigue wear to abrasive wear. With abrasive wear, substantial amounts of surface material can be removed.

4.2.5 Maintenance-induced contaminant

Contaminants can easily be introduced during routine system maintenance unless the maintenance is performed in a clean environment, and precautions are taken to prevent contaminant from getting on serviced items. For example, topping up the system with new fluid can add contaminants unless the fluid is filtered upon addition.

4.3 Liquid contaminants

After damage caused by solid particulate contamination, damage caused by the presence of liquid contamination is the next highest cause of contamination-related problems. This damage is caused either directly through corrosion or indirectly through the interaction of the liquid contamination with the hydraulic fluid. This either reduces the fluid’s effectiveness and thereby increases component wear rates, or reacts with it to produce insoluble products that can block filters, clearances, etc. Blockage under these circumstances is often rapid and unless it is detected and rectified, filtration ceases.

Water is the most common liquid contaminant in systems using mineral or synthetic fluids. Water can enter the system from the atmosphere, leaking coolers and condensation. Although most hydraulic fluids are formulated to cause water to separate so that it can settle in the reservoir and be drawn off, it is essential that the water content is maintained at levels well below the solubility or saturation level of the fluid used, at the minimum operating temperature.

Contamination by even small amounts of water in the fluid significantly lowers the load-sustaining capabilities of the fluid. This deterioration of lubrication ability is of great importance to many components in hydraulic systems. One example is that of rolling-element bearings, in which very high pressures are generated. If water is present in the hydraulic fluid, even in dissolved form, the viscosity increase required for the form of lubrication required in the bearing might not be achieved, and wear can result.

4.4 Gaseous contaminants

Nearly all fluids contain some dissolved gases. At atmospheric pressure, hydraulic fluids normally contain about 8 % of their volume as dissolved air, which, at this pressure, causes no problem. Increasing the pressure in the hydraulic fluid causes an increase in the amount of air that can be dissolved, and in low-pressure parts of the system, some of this dissolved air can be liberated in the form of bubbles, a situation frequently found downstream of pressure relief valves.

The presence of air bubbles in a system almost always causes erratic operation of the system, as it affects the stiffness (bulk modulus) of the fluid and thereby system response. Air bubbles in an inlet (suction) line of a pump reduce the volumetric efficiency and cause damage to most kinds of pumps through cavitation. Another effect often seen in high performance systems is the sudden compression of the fluid in the high pressure section of the pump, which causes the air bubbles to implode, and causing the vapour to ignite momentarily. The very high temperatures generated cause thermal stress on the fluid, leading to oxidation and nitration. A similar condition can exist downstream of metering valves; the process is known as “dieseling” and leads to the formation of gums, varnishes and even microscopic “coke” particles. These in turn can lead to lacquering of valves and plugging of filters.

5 Effects of particulate contamination and the benefits of its removal

5.1 General

It has been demonstrated that, in the majority of hydraulic systems, the presence of solid contaminant particles is the main cause of failure and reduced reliability. The sensitivity of components to these particles depends on the internal working clearances in these components, the system pressure levels and the quantity, size and hardness of the contaminants.

5.2 Failures caused by particulate contamination

Failures arising from contamination fall into three main categories:

a) sudden or catastrophic failure, which occurs when a few large particles or a very large number of small particles enter a component and cause seizure of moving parts (e.g. pumping elements or valve spools);

b) intermittent or transient failure, which is caused by contamination momentarily interfering with the function of a component. The particle(s) can be washed away during the next cycle of operation. For example, particles can prevent a valve spool from moving in one of its positions but are washed away when the valve spool is moved to a new position; or a particle can stop a poppet valve from closing properly but is washed clear during the next operation; and

c) degradation failure, which generally happens over time and shows up as a gradual loss of performance. The main causes are abrasive wear inside a component and erosion caused either by cavitation or by impingement of contaminated fluid at high velocity, all of which can cause increased internal leakage. If degradation failure is allowed to continue, it can eventually lead to catastrophic failure.

5.3 Benefits of filtration to reduce solid particulate contamination

The objective of filtration is to reduce the level of solid particulate contamination present in a system and maintain an acceptable level of cleanliness, no matter what contamination is being generated and ingressed into the system. Maintaining an acceptable level of contamination achieves the following benefits:

a) extended component life — the wear in components is reduced thus extending the useful life of the system;

b) enhanced system reliability (see 8.1) — maintaining fluid cleanliness minimises intermittent failures caused by particles jamming in critical components;

c) reduced downtime and servicing costs — the cost of replacing components is often far outweighed by lost production time and servicing costs. By increasing component life and reliability, contamination control contributes to production efficiency and reduced maintenance costs;

d) safety of operation — safety of operation results from consistent and predictable performance. Contamination control ensures that the conditions that lead to inconsistent and unpredictable operation are greatly reduced; and

e) extended fluid life — by minimizing the number of particles in the system, operating with a clean fluid can extend the life and serviceability of the system fluid by reducing oxidation, which is catalyzed by the presence of reactive particles. For example, it has been shown that the catalytic effect of a mixture of copper particles and water results in 47 times more oxidation (ageing) of the oil. This is of considerable importance when the lifecycle costs of fluid (initial, operational and disposal) are significant.

6 Evaluation of cleanliness

6.1 General

The level of cleanliness in a system varies depending on its design, assembly and operation. Later clauses describe the control necessary to maintain acceptable cleanliness levels. However, it is important to know what level of contamination is reasonable for the required reliability and life of the particular system and how these levels can be categorized.

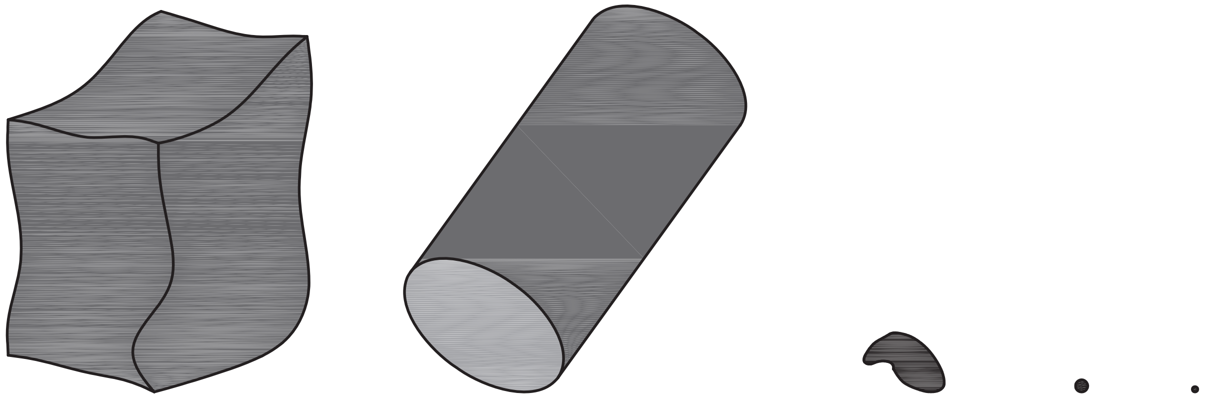
6.2 Particle size range of interest

A wide range of particle sizes can affect the performance of hydraulic components and systems. The smallest size of concern can range from 1 µm or smaller, when considering particles that cause wear by penetrating the clearances of components, to well over 1 000 µm (1 mm) in the case of large particles jamming the moving parts of components. Table 2, which is adapted from the American Society of Mechanical Engineers (ASME) Wear Control Handbook (see Bibliography), shows typical dynamic operating clearances for common hydraulic components.

Table 2 — Typical dynamic operating clearances

Component	Clearance	Component	Clearance
piston pump		servo valve	
piston to bore:	5-40 µm	spool to sleeve:	1-4 µm
valve plate to cylinder:	0,5-5 µm	orifice:	130-450 µm
gear pump		flapper wall:	18-63 µm
tooth to side plate:	0,5-5 µm	roller element bearings:	0,1-1 µm
tooth tip to case:	0,5-5 µm	journal bearings:	0,5-25 µm
vane pump		hydrostatic bearings:	1-25 µm
vane sides:	5-13 µm	gears:	0,1-1 µm
vane tip:	0,5-1 µm	dynamic seal:	0,05-0,5 µm
		actuators:	5-250 µm

The particle size range of interest presents some difficulties in perceiving and understanding the size of these particles. For most of the sizes, scientific instruments are needed to both size and count particles, as the smallest particle that can be seen with the unaided human eye is about 40 µm; see Figure 1.



Grain of salt
≈ 100 µm on each side

Diameter of a human hair
≈ 75 µm

Limit of human
vision ≈ 40 µm

5 µm
wear
particles

2 µm
wear
particles

Figure 1 — Relative sizes (diameter or longest dimension) of common particles and objects

6.3 Methods of measuring and monitoring solid particulate contaminants

Several analytical methods are commonly used to measure and describe solid particulate contaminants. Each technique produces a different piece of information about the contaminant. None produces a complete description nor is there a convenient way to translate data of one type into another. These principal methods are:

a) gravimetric concentration: determines contaminant mass per volume of fluid; ISO 4405 provides a method;

NOTE The inaccuracies inherent in this method make it unsuitable for evaluating the fluid cleanliness of modern hydraulic systems. It is more suited to analyze samples in which relatively large weights are involved, for example, the evaluation of component cleanliness.

b) optical particle counting (automatic or manual): determines size and number; ISO 11500 and ISO 4407 provide methods;

c) ferrography: primarily indicates the magnetic metal content of the contaminant;

d) spectroscopy: determines elemental composition of the contaminant;

e) filter blockage: semi-quantitative determination of size and number of particles; ISO 21018-3 provides a method.

ISO 21018-1 provides a more comprehensive list of contaminant monitoring techniques and the advantages and limitations of each method.

7 Coding systems for expressing level of solid particulate contamination

7.1 General

The output of most of the particle monitoring instruments is the number of particles at certain sizes. In hydraulic systems, these can vary considerably from single figure values in the case of larger particle sizes in very clean systems to many millions in the case of dirty systems. The communication of these varied numbers at the different sizes is often confusing, and to overcome this, several coding systems have been developed to simplify the reporting of contamination data. The basis of these codes is the sub-division of the counts into broad based bands and assigning a code number to each band. The most commonly-used methods currently in use in industry are described in the following subclauses.

7.2 ISO 4406 coding system

For industrial applications, the ISO 4406 coding system for expressing the level of contamination by solid particles is the preferred method of quoting the number of solid contaminant particles in a fluid sample. The code is constructed from the combination of three scale numbers representing the concentration of particles at three specific particle sizes.

The unit of particle size depends on the sizing parameter used in the analysis, whether it is the longest dimension (optical microscopic method) or equivalent spherical diameter (automatic particle counter method). In the ISO 4406 coding system, particle sizes expressed in µm indicates that the particle size distribution was determined using a microscope, and particle sizes expressed in µm(c) indicates that the particle size distribution was determined using an automatic particle counter (APC) calibrated in accordance with ISO 11171. In the ISO 4406 coding system:

a) the first scale number represents the number of particles in a millilitre sample of the fluid that are larger than 4 µm(c);

b) the second number represents the number of particles larger than 5 µm or 6 µm(c); and

c) the third number represents the number of particles that are larger than 15 µm or 14 µm(c).

Because not every application requires that all three sizes be specified, or in those cases where the contamination monitor is unable to provide this information, there are three variants on the three-number code, in accordance with the following examples:

a) 22/19/14, which indicates that all three particle sizes are have been counted;

b) */19/14, which indicates that there are too many particles equal to or larger than 4 µm(c) to count; and

c) -/19/14, which indicates that the application does not require that particles equal to or larger than 4 µm(c) be counted.

It is recognised that in very clean fluids, the number of particles being counted, even in 100 mL of fluid sample, can be too low to be statistically reliable. Therefore, if fewer than 20 particles are counted for a particular size, ISO 4406 requires that the scale number be preceded by ≥ to signify this, e.g. 16/12/≥10.

Note that the ISO 4406 system differs from other cleanliness coding systems in that it does not include codes for particle sizes larger than 15 µm (see 7.3). This is because most hydraulic systems incorporate filters and, as a result, there are very few of these larger particles. Because there are so few, it is unlikely that the number of these larger particles counted will be consistent from sample to sample, so trending or comparing data at these particle sizes becomes meaningless.

Microscope counting examines the particles by longest dimension (not equivalent area, as an APC does) and the code is given with a dash and two scale numbers, e.g. -/19/14. The particle sizes reported are at 5 µm and 15 µm, which are equivalent to the 6 µm(c) and 14 µm(c) sizes determined using an APC. See ISO/TR 16386 for a description of differences in particle counting and sizing methods.

7.3 NAS 1638, SAE AS4059 and ISO 11218 coding systems

The NAS 1638 cleanliness coding system was originally developed in 1964 to define contamination classes for the contamination contained within aircraft components. The application of this standard was extended to non-aerospace hydraulic systems mainly because nothing else existed at the time, and it is still widely used. NAS 1638 was made inactive in May 2001 in favour of SAE AS4059, which is SAE's modernization of the NAS 1638 coding system and which has been adopted as ISO 11218 for aerospace hydraulic systems.

As with the ISO 4406 code, the SAE AS4059 and ISO 11218 codes are based on the number of particles at specific sizes. The coding system defines the maximum numbers of particles permitted in each size range, and the result is usually expressed as a single digit class number based on the highest class level obtained for all particle sizes measured.

ISO 4406 is recommended for expression of contamination levels for non-aerospace hydraulic systems, so users of this technical report can consult the respective standards if further details are desired about the other methods.

8 Setting required cleanliness levels (RCLs) for a hydraulic system

8.1 The amount of contamination that a system can successfully operate with depends upon two factors:

a) the relative sensitivity of the components to contaminant, and

b) the level of reliability and component service life required by the system designer and user.

This was established in a UK Department of Trade and Industry (DTI) survey of hydraulic systems (see Bibliography), which showed an inverse relationship between the contamination level in the hydraulic fluid and the system reliability experienced, as shown in Figure 2.

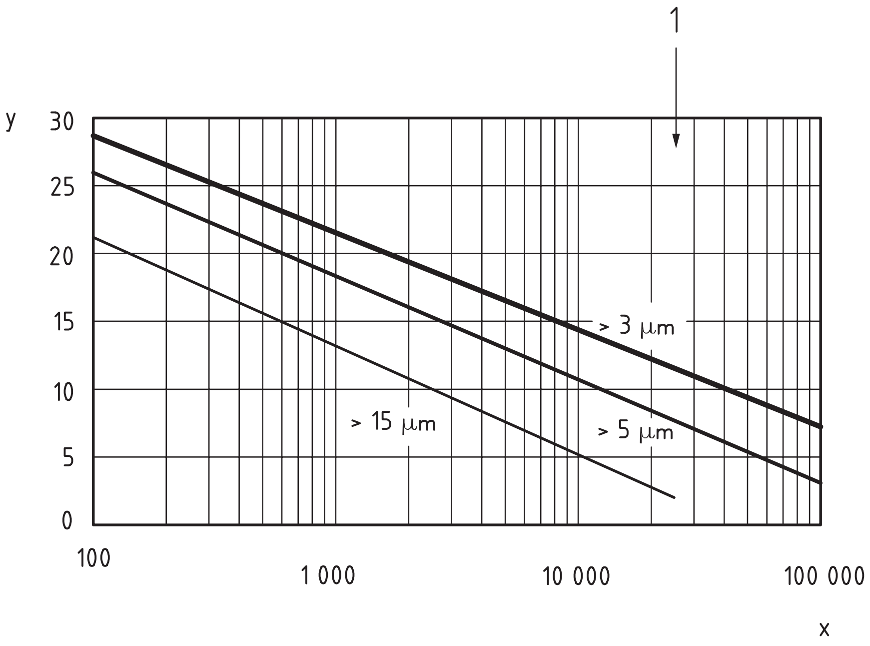
A system designer needs to select the most appropriate fluid cleanliness level for the system, known as the required cleanliness level (RCL). The importance of the RCL cannot be overemphasised, as it is the basis of system cleanliness management; it

a) is used to dictate the cleanliness of components at the build stage;

b) defines the level of cleanliness at delivery; and

c) provides the basis for setting maintenance action levels in service.

The subsequent subclauses describe four methods for selecting an RCL.



Key

x reliability (MTBF, hours)
y ISO Code
1 DTI Study, 1984

Figure 2 — Relationship between ISO 4406 code and reliability

8.2 The first and preferred method for selecting the RCL is a comprehensive method based on guidelines incorporating the specific system operating conditions. The advantage this method has over others is that it accounts for the life and reliability required by the user for his system, and not the general requirements for a machinery group. This method is described in British Fluid Power Association Document P5. The RCL determined is based on the following parameters:

a) operating pressure and duty cycle;

b) component sensitivity to contamination;

c) life expectancy;

d) cost of component replacement;

e) downtime;

f) safety liabilities; and

g) environmental considerations.

The attributes of the system and its operation are reviewed and used to establish a weighting or score. These are then accumulated to give the RCL. The level selected is considered to be the maximum permissible level for reliable operation under the circumstances. If it is exceeded, then corrective actions can be implemented, otherwise the contamination control balance is disturbed, and component wear rates can accelerate.

8.3 The second method is for the system designer to use his own experience or consult with others with experience and similar requirements. In many cases, this information is supplied by a filter manufacturer that has access to such information for such benchmarking. The system designer uses caution when applying others' experience, as the operating conditions, environment, and maintenance practices might not be the same.

8.4 The third method is to use studies and resulting data such as Figure 2. Again, the system designer uses caution, as these recommendations are usually very general in nature and might not address the application specifically.

8.5 The fourth method is to contact the manufacturer of the most contaminant-sensitive component in the system for recommendations. Most component manufacturers know the detrimental effect that increased contamination levels have on the performance of their components and issue maximum permissible contamination levels. They state that operating components with fluids that are cleaner than those stated can increase life. However, the diversity of hydraulic systems in terms of pressure, duty cycles, environments, lubrication required, contaminant types, etc., makes it almost impossible to predict the component's service life with more precision than what can be reasonably expected. Furthermore, without the benefits of significant research and the existence of standard component contaminant sensitivity tests, manufacturers that publish recommended cleanliness levels that are cleaner than their competitors might be viewed as having a more sensitive product.

9 Cleanliness management concepts

9.1 System design considerations

9.1.1 Although hydraulic filters are critical in maintaining the cleanliness of an operating system, simply applying a filter and ignoring other recommended practices is inadequate for completely protecting the system from contamination. Since contamination comes from a wide variety of sources, a comprehensive cleanliness management program addresses each of these sources and emphasizes methods of minimizing contaminant entry and damage as well as methods for contaminant removal.

9.1.2 Typical processes used to minimize contaminant entry and damage include:

a) design and manufacture of components and systems that are tolerant of contamination;

b) selection and use of adequate filters; see Clause 12;

c) use of effective reservoir air breather filters, joints, and external seals;

d) repair and maintenance procedures that minimize the entry of contamination; and

e) maintenance of cleanliness throughout manufacture and assembly; ISO/TR 10949, ISO 16431 and ISO 18413 cover component and system cleanliness measuring and reporting methods; ISO 23309 covers flushing methods of cleaning lines in hydraulic systems.

9.2 Monitoring system cleanliness

9.2.1 General

It is recommended that the system cleanliness level is monitored after one week's initial operation and thereafter in two month's time. The selected filtration rating is acceptable if the RCL is achieved within this time. If the RCL is not achieved, then either a filter with a finer filtration rating or additional filters can be required. The frequency of monitoring is then selected on the basis of the stability of the system cleanliness level.

Regular checks on the fluid cleanliness level ensure that the contamination control system is working satisfactorily, and that the specified level of cleanliness is being maintained. This can be achieved either by connecting an on-line cleanliness monitor or by taking a fluid sample from the system and analysing it off-line in a laboratory.

It is also recommended that the physical and chemical condition of the hydraulic fluid, in addition to its cleanliness, be monitored. This provides information necessary to ensure that the necessary fluid properties are maintained.

9.2.2 Fluid sampling

In order to establish the condition of the fluid, it is necessary to extract a representative sample of the system fluid. ISO 4021 provides recommended sampling procedures. When monitoring is done on a regular basis, samples are taken from the same sampling point, and after approximately the same operating sequence or time, beginning typically more than 1 h after start-up.

The importance of correctly taking the sample cannot be overemphasised because modern hydraulic systems are typically designed to operate with very clean fluids. As a result, there is a high probability that contamination level could be measured inaccurately if inappropriate techniques are used. This could greatly increase operational costs if corrective actions result from a non-representative result. Improper sampling also makes trending data almost impossible. As modern hydraulic systems have very clean fluids, on-line monitoring is recommended to minimize errors introduced from sample valves and bottles. See ISO 21018-1 for on-line monitoring considerations.

If bottle sampling is used, it is essential to use only sample bottles that have been cleaned and verified in accordance with ISO 3722. Modern hydraulic systems featuring highly effective filters have fluid cleanliness levels that approach that of the pre-cleaned sample bottles themselves. The use of inadequately cleaned bottles can greatly increase the contamination measured.

9.3 System maintenance for cleanliness management

9.3.1 Responsibilities

Regular and effective maintenance is essential if the desired system reliability is to be achieved. It is the responsibility of the original equipment manufacturer to provide adequate maintenance procedures for the equipment being supplied. Effective detailed procedures take into account the duty cycle of the system on an individual basis and the environment in which the system is operating.

The end user is responsible for ensuring that adequate servicing facilities are available and that routine maintenance is carried out.

9.3.2 Disciplines

The maintenance of a hydraulic system for cleanliness management is usually covered by seven basic disciplines:

a) inspection of the system, while operating, for leaks and filter blockage;

b) maintaining the level of the fluid in the reservoir within the limits stated by the manufacturer;

c) changing disposable filter elements or cleaning strainers;

d) taking samples of the fluid;

e) monitoring the fluid condition;

f) monitoring the mechanical condition; and

g) identifying corrective action.

9.3.3 Maintenance procedures

Written maintenance procedures typically accompany every new piece of hydraulic equipment and contain at least the following information related to filtration:

a) types and quantities of filter elements;

b) filter element change procedures with an appropriate recording system for such changes;

c) required system cleanliness level and intermediate action levels;

d) recommended method of fluid sampling;

e) frequency of fluid condition checks;

f) type of fluid required;

g) instructions about addressing leaks; and

h) corrective actions to be taken in the event that an action level or the RCL is exceeded.

9.3.4 Changing or cleaning filter elements

It is most important that the disposable filter element is changed and or the strainer is cleaned as soon as its differential pressure device shows that the element is becoming clogged or that a specified differential pressure has been reached.

It is recommended that filters always be fitted with a differential pressure device or some means of showing when they are becoming blocked. However, if a filter does not contain such a device, it is vitally important to change the element at intervals recommended in the maintenance manual, and it is always preferable to change such an element too frequently rather than to allow it to run in a bypass condition that might remain unnoticed.

Ensure that replacement elements are of the correct type and rating. Using an element with too coarse a rating cannot maintain the desired fluid cleanliness level. If an element that is too fine or whose differential pressure rating in the clean state is too high is installed, it can start bypassing prematurely and become ineffective.

If a fill filter is fitted on the reservoir, it is typically inspected regularly and if significantly contaminated, it is removed, cleaned, dried and refitted. A damaged fill filter is usually discarded and a new one installed.

Filter elements made of wire mesh and designated as cleanable, including pump inlet strainers, can be cleaned by reverse flushing with a very clean solvent. However, if the mesh is fine, immersion in an ultrasonic bath can be required to loosen contaminant trapped in the mesh before final reverse flushing. Ensure that contamination is not transferred from the dirty to the clean side. The filter manufacturer’s recommended cleaning procedures can be followed. A cleanable filter element can be cleaned only a finite number of times before replacement is necessary. Cleanable filter elements generally have a coarse filtration rating, typically > 25 µm(c) where $\beta = 200$ when tested in accordance with ISO 16889.

Any seals fitted to the filter are typically inspected and replaced if damaged or hardened.

9.3.5 Filling the system with fluid

Considerable quantities of contaminant can be added during a normal system fluid fill process unless extreme care is taken in filling up a system, and the new fluid is filtered.

10 Filters

10.1 Mechanisms of filtration

10.1.1 Particle capture and retention

The two processes by which fluid borne particles are captured and retained by a filter are called interception and adsorption.

Interception occurs when the particle is physically too large to pass through the pore that is in front of it, is taken from the flow stream and typically securely held in the filtration medium. Sieving is an example of interception. Whether or not the particle is securely held and does not get released as flow conditions change depends on the pore size distribution, the way that the fibres of the filtration medium are bonded together and the strength of the fibres. The interception mechanism predominates in most high-quality hydraulic filters.

Adsorption is a process whereby particles are taken from the flow stream and held through some form of attractive surface force such as electrostatics or van der Waals forces. Although these forces can be quite strong, they only act over extremely short distances, and the capture and retention efficiencies are relatively low. Variations in flow, viscosity and vibration, which are typical in hydraulic systems, can act to cause particles captured by adsorption to be subsequently released (desorption). For this reason, adsorption typically is not the predominant capture mechanism in hydraulic filtration.

10.1.2 Particle transport mechanisms

Transportation of the particle to the fibre occurs predominantly by two main mechanisms. In one, the particle passes close to the fibre and if the attractive force is greater than the flow force, the particle is drawn to the fibre and is held on contact. In the other, called inertial impaction, a particle is unable to remain in the fluid streamline as the fluid moves around the fibres in the medium and the momentum of the particle is sufficient to cause it to deviate from the fluid flow stream and to collide with a fibre where it is then held in place. Other, much less significant, transport mechanisms are gravitational interception, in which the fluid is static, and diffusional interception (or Brownian motion), which is usually too weak to be effective in liquids but is more dominant in gasses. These mechanisms produce particle displacements that are generally insignificant compared to those generated by the moving fluid. Nevertheless, if the fluid at the surface of the medium becomes quiescent, larger particles can gravitate, and smaller ones diffuse, into contact with the medium.

10.2 General filter concepts

10.2.1 Filter operation and life

There are three identifiable phases in the life of a filter:

a) an initial short cleanup phase in which the filter reduces the number of particles, depending on the cleanliness level produced by the previous filter in the system;

b) a relatively long stable phase in which an approximate balance is maintained between particles ingressed into, and removed from the system; and

c) a relatively short end phase in which the filter medium becomes plugged and imposes a restriction to the fluid flow, and the differential pressure across the filter rapidly rises.

The level of fluid cleanliness depends on the combination of the filter’s contaminant removal characteristics, the system’s contaminant ingression rate, and operating conditions. As these change, the fluid cleanliness level also changes and can continue to vary throughout the filter’s service life.

10.2.2 Common misconceptions about filtration

A number of significant misconceptions about filtration persist and are addressed below:

a) *Misconception: Filters are screens composed of uniformly sized pores*.

Fact: Modern hydraulic filters, except, possibly, strainers, are not composed of uniformly sized pores, and particles are not uniform in shape or spherical. Thus it is possible for particles that are larger than the average particle size to pass through a filter medium by virtue of the presence of pores that are larger than average or because of the orientation of the particle in the fluid stream as it passes through a pore.

b) *Misconception: Particles smaller than the filter’s pore openings are not captured in a filter medium*.

Fact: Sieving (that is, the capture of a particle because it is too large to pass through the pore) is not the only mechanism by which particulate contaminants are captured. Contaminants can also be captured by simply coming into contact with a filter fibre and then being held by attractive forces between the contaminant and the fibre. As a result, contaminant particles smaller than the pore opening are often captured.

c) *Misconception: Adding the proper filter to a hydraulic system ensures that contamination is controlled*.

Fact: Filters alone are not substitutes for an effective contamination control program. While filters remove contaminants circulating within the system, they do not eliminate all the sources of the contamination, nor do they prevent damage from occurring before the contamination is trapped.

d) *Misconception: A micrometre (also called a micron) rating defines the filter performance*.

Fact: Stand-alone filter micrometre or micron ratings have little or no relation to the actual performance of a filter and are often selected arbitrarily. Although terms such as nominal rating, absolute rating, or even filter rating are commonly used, these terms have no official standing within the industry, unless defined and tied to a designated filter test standard and test conditions. The ratings of filters used in industrial hydraulic systems are typically obtained by a standardized test (see Clause 11).

e) *Misconception: The retained contaminant capacity of a filter element is related to filter service life*.

Fact: The solid contaminant retained capacity of a filter element is not a measure of filter service life. It is the amount of standardized contaminant that is captured and retained by the filter during a controlled laboratory test causing it to plug. The capacity cannot be directly related to the filter life in actual service because of the widely different operating conditions, maintenance practices and types of contaminant seen in actual service.

10.2.3 Filter performance parameters

The characteristics most commonly used to describe filter performance are filter efficiency (sometimes expressed as a filtration ratio), solid contaminant retention capacity (sometimes referred to as dirt capacity) and clean element differential pressure.

Filter efficiency relates to the cleanliness level that can be achieved and how quickly it is established. Solid contaminant retention capacity relates to the amount of contamination that can be captured by the filter before the differential pressure reaches a designated value. The clean element differential pressure relates to the amount of restriction to flow and energy consumed during operation and needs to be considered during the initial design of the system.

There are two other characteristics of a filter which are sometimes ignored but are also extremely important in its ability to maintain system cleanliness throughout its life:

a) the performance of the bypass valve, measured in terms of its response, hysteresis, leakage rates and stability, and

b) the compatibility of the filter with the system fluid and operating conditions without any mechanical or chemical deterioration.

All of these characteristics are determined using standardized laboratory test methods as discussed in Clause 11. Because the steady-state, controlled conditions used in laboratory tests rarely exist in the field, the system designer needs to be careful in how this data generated by laboratory testing is used. Increased or fluctuating flows, changes in fluid viscosity, variable contaminant ingression rates and several other factors not duplicated in all laboratory tests can affect filter performance in ways that are not fully predictable without testing under actual or simulated operating conditions. As it is not possible to replicate the wide range of operating conditions in a laboratory test, the tests discussed in Clause 11 have been designed to be as severe as practical. It is recommended that most, if not all, of them be used to draw up filter specifications.

10.2.4 Filtration as a statistical process

Modern filters feature a fibrous filter medium that creates a range of pore sizes, so that the removal of particles can be represented using statistics. Likewise, fluid contaminants come in a wide range of sizes and shapes. At the simplest level, filtration therefore involves an analysis of the probability that the right-sized particle approaches the right-sized pore to effect a capture.

Such an analysis is complicated by the tendency of fluids and the particles carried by them to seek the path of least resistance through the medium (e.g., the largest pores), which can decrease the likelihood of capture.

However, two particles cannot occupy the same space simultaneously, which can lead to particle-to-particle interactions that can make capture more likely. Finally, particles that are smaller than the pore opening can be captured by adsorptive mechanisms (as discussed in 10.1).

Given this background, any in-depth statistical analysis typically considers:

a) the distribution of pore and particle sizes,

b) the fluid forces acting on the particle to affect its orientation,

c) the possible interactions between particles competing for passage through the same pore, and

d) the presence of a variety of particle capture mechanisms.

Such a detailed analysis is not practical, but the following general conclusions can be drawn:

a) a greater proportion of large particles are captured than of small ones;

b) some particles can find their way through the filter medium on each pass;

c) while no particle can escape capture forever, re-release or desorption of particles is also possible; and

d) as pores become blocked, changes in fluid flow paths and particle interactions at unblocked pores can affect filter performance.

10.2.5 Filtration as a dynamic process

It has long been recognized that filtration is also a dynamic process affected by fluid flow variations, the migration or release of previously trapped particles, and the changing shape and composition of the particles suspended in the fluid.

Few, if any, hydraulic systems have constant flow rate, pressure or viscosity. As a result, the filter medium is subjected to flow rate surges and flow reversals and to pressure spikes not found in laboratory tests which affect filter performance in the actual end use application. Standardized laboratory test methods exist or are under development which can ascertain the filter performance under dynamic conditions (see SAE ARP4205). Testing has shown that the following generalities usually hold true for the effects of system dynamics on filter performance:

a) large particles are much easier to capture and retain than small ones;

b) filter efficiency is highest with steady-state flow rates and is generally lower as both the magnitude and rate of flow rate cycling is increased;

c) vibration can lower the effective filter efficiency;

d) flow reversals can cause high filter element differential pressure in the reverse flow direction, often resulting in “ballooning” or permanent damage, and are to be avoided; and

e) even minor internal leakage around the filter element can significantly degrade filter performance.

10.3 Types of filters and filter elements

Filters can generally be classified into one of the following categories:

a) pressure line filters, designed to withstand full system pressure and the duty cycle at the location;

b) return line filters, intended for lower pressure applications such as in return lines;

c) off-line filters, for use outside the main system, usually with a separate fluid recirculation system;

d) suction line filters or strainers, for use in the pump suction line; and

e) reservoir filters or strainers, to prevent contaminants or water vapour from entering reservoir.

Hydraulic filter elements can generally be put into two categories:

a) filter elements designed for low differential pressure, which constitute the majority of filter elements used; as a result of being designed for low differential pressure, they are usually protected by a bypass valve;

b) filter elements manufactured to be much stronger to withstand a high differential pressure, usually set at or near the system pressure; these are of the non-bypass type.

See Clause 12 for recommendations for selection and location of each type of filter and filter element.

10.4 Filter accessories

10.4.1 Differential pressure devices

As fluid flows through a filter, a differential pressure occurs. Under normal conditions, this differential pressure can be used to estimate the condition of the filter and its remaining useful life. Differential pressure devices, also known as filter blockage indicators, are an essential part of system management as they give warning of an impending filter blockage or high viscosity condition, both of which can result in a subsequent bypassing condition. For proper cleanliness management, filters are most often fitted with a differential pressure device or some other means of showing when they are becoming blocked. It is strongly recommended that such indicators be fitted to ensure continued control over contamination and the protection of the system concerned.

Differential pressure devices come in a variety of forms:

a) visual indicators, with either a pop-up button or other such device that gives visual indication of high differential pressure or impending bypass;

b) electrical indicators, with either local or remote warnings through lights, sirens, etc.; and

c) continuous reading devices, where there are continuous analogue or digital displays of differential pressure.

10.4.2 Filter valve arrangements

10.4.2.1 Bypass valves

Differential-pressure-actuated bypass or relief valves protect the filter element from excessive differential pressure generated by blockage, high viscosity conditions (e.g. cold starts), surges, increased flow rate, etc., by diverting the flow away from the element directly to the outlet port. Effective valves respond quickly and do not impose additional differential pressure upon opening as the bypassed flow rate increases. Bypass valves must have extremely low internal leakage when not actuated; otherwise, the effective performance of the filter element is severely degraded.

Concern about using unfiltered hydraulic fluid during a short-term (i.e. lasting no more than several hours) bypass due to cold fluid start-up conditions is generally unwarranted. The fluid was essentially filtered during its last pass through the system and, unless the system is in a major failure mode or a service repair has just been performed, contaminant generation and/or ingression rates are typically low enough that one need not be concerned about short-term filter bypass. Furthermore, if the filter has been correctly sized, bypassing is only partial, as a proportion of flow always passes through the element.

Concern is warranted, however, if the bypass is caused by filter clogging or if an undersized filter is used. Unless corrected, filter bypass can then persist until the next maintenance interval, with damaging consequences that might not be readily apparent.

The system designer needs to clearly understand the functional operation and performance of the bypass mechanism. Slow response times can limit bypass valve effectiveness and impose unnecessary stress on the filter element, which can lead to fatigue damage. Internal leakage or premature actuation of the bypass valve can degrade overall filter performance. In addition, good practice would prevent fluid flow during bypass from washing contaminants from the filter back into the system.

A correctly applied bypass valve exhibits flow/differential pressure characteristics that prevent it from imposing significant additional differential pressure on the filter element as the flow rate increases (also known as pressure override); otherwise the stress levels increase.

A correctly applied bypass valve also tracks the differential pressure and open and close as the differential pressure increases and decreases, and the two curves representing these opening and closing characteristics ideally overlay each other. The difference between the opening and closing characteristics is called hysteresis and can indicate a design fault. For instance, a valve with a sticky valving element exhibits a high level of hysteresis and typically will not close until a very low differential pressure is reached, thereby resulting in unnecessary bypassing.

10.4.2.2 Reverse flow valves

Reverse flow valves act as a normal bypass valve in the normal direction of flow but block flow in the reverse direction of flow and divert it away from the filter element to another port. Rapid operation is essential if the filter element is designed to be unidirectional, to prevent reverse flow through the element, which causes substantial damage.

10.4.2.3 Anti-back-flow valves

Anti-back-flow valves are designed for return line filters that are mounted below the surface of the fluid in the reservoir where there is a possibility of back flow when the element is changed. A valve closes the outlet port (and sometimes also the inlet port) when the element is removed and is only opened when the element is replaced.

10.4.2.4 No-element/no-flow valves

As their name suggests, no-element/no-flow valves require that an element hydraulically connect the inlet and outlet ports in a filter and are used in very critical systems. These valves have to withstand full system pressure without leakage and are sometimes seen in aerospace systems but rarely in industrial hydraulic systems.

11 Filter evaluation

11.1 General

The primary goal of a laboratory filter evaluation is to determine the level of cleanliness that a filter can establish and maintain in an actual operating system throughout its life, and especially as it becomes blocked, as this is the condition of highest stress. In addition, a complete test protocol evaluates other parameters relating to material compatibility, and the filter's ability to withstand all the stresses of an operating system. Recognizing that the observed filter performance is affected by system parameters (e.g. flow rate dynamics, vibration, contaminant ingression rates, etc.) that change from one application to the next, laboratory tests use standardized conditions to measure filter performance under a given set of conditions.

Unfortunately, there is presently no simple way to directly use results obtained from standardized laboratory test methods to fully predict field results for reasons discussed earlier. Consequently, the system designer is always advised to consult with a filtration specialist for guidance on proper filter selection for a particular application.

11.2 Laboratory filter test methods

A number of ISO standardized test methods have been developed to measure various properties of a filter, filter element and/or filter medium. In general, these tests can be grouped into three broad categories based upon: the physical properties of the element, the physical properties of the complete filter (i.e., filter element and its housing), or the performance of the complete filter.

Specification of performance is given by filter manufacturers in their catalogues, and this information is usually obtained using the various standardized test methods that have been developed for hydraulic filters. A brief explanation of each procedure is given in Table 3.

Table 3 — Filter evaluation standards

Standard number	Subject	Additional information
ISO 2941	Collapse/burst resistance	Used to evaluate the ability of the element to maintain integrity when subjected to a stated differential pressures
ISO 2942	Fabrication integrity	Used to assess the quality of construction of the element by looking for leakage areas
ISO 2943	Material compatibility	Evaluates the compatibility of the materials used in the element and housing with the hydraulic fluid. It involves soaking the element (or material) for 72 hours at 15 °C above the maximum, and/or 5 °C below the minimum, stated temperature of use
ISO 3723	End load	Evaluates the ability of the element to withstand compressive force without sustaining loss in integrity after an ISO 2943 compatibility test. It was originally designed for spring loaded elements or those secured to a housing using a tie bar, and is not typically applied to modern O-ring located and sealed elements
ISO 3724	Flow fatigue using particulate contaminant	Used to evaluate the element’s ability to sustain cyclic flow conditions when in a near blocked condition. The test is performed over a designed number of cycles
ISO 3968	Flow rate/differential pressure characteristics	Determines the pressure loss characteristics of the housing, element and any valves used in the housing. It also includes tests to measure the leakage and other performance characteristics of the bypass valve
ISO 16889	Multi-pass performance test	Determines the filtration performance and rating over a wide particle size range, and also gives a measure of its solid contaminant retention capacity for the specific test dust used
ISO 23181	Flow fatigue using high viscosity fluid	Used to evaluate the element’s ability to sustain cyclic flow conditions at a stated differential pressure. The test is performed over a designed number of cycles. This test is similar to ISO 3724, except for the method to achieve high differential pressure
ISO 16860	Differential pressure device test	Evaluates operating characteristics of a differential pressure device
ISO 10771-1	Metal container fatigue test method	Can be used to test metal filter housings
ISO/TR 10771-2	Metal container fatigue rating method	Can be used to determine and express a fatigue rating for metal filter housings

Because the multi-pass performance test gives so much information about filter performance, it is sometimes used alone to specify a filter for a specific application. ISO 11170 was developed to avoid the limitation of basing a filter selection policy on a single test method by providing a complete filter qualification test programme based on testing three elements using relevant ISO test method standards, as shown in Table 4.

Table 4 — Test sequence from ISO 11170 for verifying performance characteristics

Element 1	Element 2	Element 3
ISO 2942	ISO 2942	ISO 2942
ISO 2943	ISO 2943	ISO 2943
ISO 2942	ISO 2942	ISO 2942
ISO 16889	ISO 3723	ISO 3968
ISO 2941	ISO 2941	ISO 3724
ISO 2942	ISO 2942	ISO 2941
		ISO 2942

12 Filter selection process

12.1 General

Selection of filtration for a hydraulic system involves the following four steps:

a) system definition and setting of the RCL;

b) selection and location of filters;

c) sizing of filters; and

d) assessment of candidate filters.

12.2 System definition and setting of the RCL

12.2.1 The system designer identifies the components and their associated required cleanliness levels. Usually this includes reviews of component clearances, criticality of the component in the system and of the system itself, and similar designs that have proved successful.

12.2.2 The system designer determines or estimates the following:

a) components used and their contaminant sensitivity;

b) reason for fitting the filter, either for component protection or wear control;

c) contamination ingression rates and sources. Systems located in dusty or harsh environments are more likely to ingest larger amounts of abrasive contaminant. Not only do filters need to be correctly specified to achieve the cleanliness levels required, they also require sufficient solid contaminant retention capacity to ensure that an acceptable service life is achieved;

d) feasible and preferred filter locations;

e) allowable differential pressure or pressure available (necessary for return line or low pressure applications);

f) fluid flow rates and surges — the correctly applied filter is sized to handle the maximum flow rate experienced;

g) operating pressures, including pressure transients and spikes — the correct application of a filter takes into account the impact of the operational duty cycle on fatigue;

h) fluid type and viscosity over entire range of operating temperatures and pressures — probably the most important consideration that is often forgotten. The fluid within the system not only has an impact on material compatibility (seals, housing, etc.) but also with its variable property of viscosity with temperature and pressure;

i) service interval requirements.

12.2.3 Using this information, the system designer then selects a required cleanliness level for the system consistent with the system design objectives. See Clause 8 for more information about this process.

12.2.4 When the RCL cannot be clearly identified and verified by data, the system designer typically relies on past experience with similar systems modified to consider the unique aspects of the new system being designed.

12.2.5 At this point, the system designer is now in a good position to benefit from discussions with a filtration specialist.

12.3 Selecting the minimum recommended filter rating

12.3.1 General

This guide to the selection of a filter to provide the RCL chosen in 12.2 works on the assumption that the higher the level of contamination in the system's environment, the greater amount gets ingressed into the system. Thus to maintain the selected RCL, the filter installed in a system with high ingression requires a higher efficiency of particle removal than if the level of environmental contamination is lower. The expected level of ingression is selected and used to select the filter's performance characteristics.

As it is not possible to precisely define the operating parameters of a hydraulic system or to predict how a filter will perform in that system, the ability of the filter selected to provide the selected RCL can only be confirmed by analysing the filter's performance during use.

12.3.2 Procedure

12.3.2.1 Evaluate the environmental contamination level from Table 5 and select the conditions that best describes the system operating environment.

Table 5 — Environmental contamination levels and factors

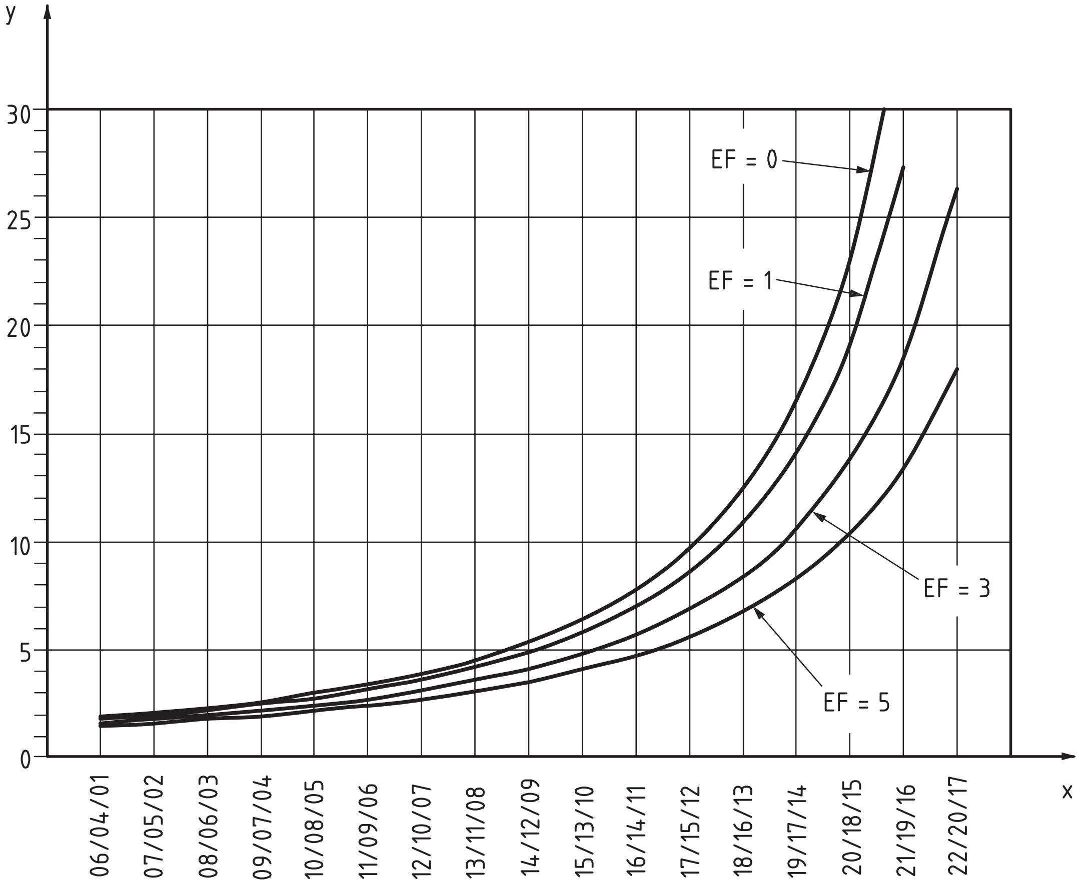
Level of environmental contamination	Examples	Environmental factor (EF)
Good	Clean areas, laboratories, systems with few contaminant ingression points, systems with fill filters and appropriate reservoir air breathers	0
Fair/low	General machine shops, lifts, systems with some control over contaminant ingression points	1
Poor	Systems with minimal control over operating environment	3
Hostile/high	Systems with potential for high contaminant ingression, for example, those in foundries, concrete plants, quarries, component test rigs	5

12.3.2.2 Select the environmental factor from Table 5 that corresponds to the environmental contamination level chosen.

12.3.2.3 Using Figure 3, locate the RCL on the x-axis and draw a vertical line upwards to intersect the line with the corresponding environmental factor, EF, determined in 12.3.2.2.

12.3.2.4 Draw a horizontal line to y-axis and read off the recommended minimum filtration ratio in µm(c), where $\beta = 200$, determined in accordance with ISO 16889. This represents the coarsest filter rating for this application.

12.3.2.5 Confirm the filter selection by analysing the filter's performance during system operation (see 12.7).



Key

x required cleanliness level (RCL), expressed in accordance with ISO 4406

y recommended minimum filtration ratio, µm(c), where $\beta = 200$

Figure 3 — Selecting the recommended minimum filtration ratio

12.4 Filter location

12.4.1 General

There are many locations for fitting filters in hydraulic systems, and the potential positions as shown in Figure 4 are discussed in 12.4.2 through 12.4.6. Wherever the filter is located, it is essential that it is easily seen so that indications of the differential pressure device or filter clogging indicator can be observed, and it is accessible so that the element can be readily changed.

While hypothetically there is an optimum location for each filter, in practice, the location is often determined by other factors such as space, serviceability, product line similarity, etc. Ideally, the filter is positioned where

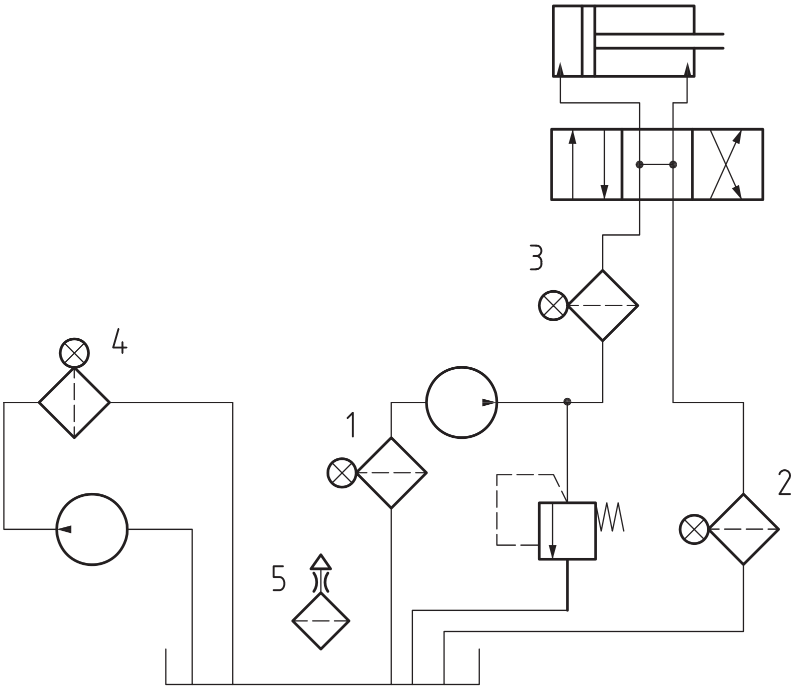
a) it can be easily monitored and serviced,

b) it is well-protected from accidental spills and siphons,

c) it provides adequate protection to critical components from a pump failure, and

d) flow rate surges or backflows that can dislodge contaminants from the filter medium are minimized.

The location of the filter ultimately depends upon the reason for installing it. If it is for direct protection of a specific component, the filter is installed immediately upstream of the component concerned. If it is installed for control over potential sources of contamination, then it is installed downstream of that source. If it is for general contamination control, then it can be installed in any of the lines that see the majority of the flow.



Key

1 suction line filter/strainer
2 return line filter, in-line (shown) or reservoir-top
3 pressure line filter
4 off-line filter
5 reservoir air breather

Figure 4 — Potential locations for hydraulic filters

12.4.2 Suction line filters

A filter or strainer can be located in the pump inlet line to protect the pump from large debris from the reservoir. It is advisable to check with the pump manufacturer before any type of filter is fitted to the pump inlet line. If this type of filter is fitted it is recommended that it is positioned outside of the reservoir where it can easily be seen and easily changed. The advantages and disadvantages of using suction line filters are:

a) Advantages

   1) Suction line filters provide some protection of the pump.

   2) Suction line strainers are inexpensive to purchase.

b) Disadvantages

   1) There is a risk that suction line filters might cause cavitation.

   2) There is no downstream protection for other critical components.

   3) These filters require a larger surface area to prevent too high a differential pressure.

   4) These filters might be too coarse to provide any real protection or contamination control.

   5) It is usually difficult to change suction line filters and to know if and when they are clogged, as they are often located in the reservoir, which usually needs to be drained to allow inspection and replacement.

12.4.3 Return line filters

Return line filters are commonly used and can be either fitted in the return line or in or on the reservoir. The advantages and disadvantages of using return line filters are:

a) Advantages
   1) Return line filters control contamination generated by components and ingressed through seals.
   2) These filters protect the reservoir.
   3) These filters are less expensive because they are designed for use at lower pressures.
   4) These filters are available in a full range of filter ratings.
   5) These filters both protect components and control wear.

b) Disadvantages
   1) Return line filters provide no direct protection of the system components.
   2) These filters need to be sized for flow rate surges from cylinders and accumulators.
   3) These filters need to be carefully selected to avoid undue back pressure on components.

12.4.4 Pressure line filters

Pressure line filters are located directly downstream of the system pump and/or directly upstream of a critical component to provide main system protection and last-chance protection from debris generated by the pump. Pressure line filters can be either the non-bypass type or contain a bypass valve. The advantages and disadvantages of using pressure line filters are:

a) Advantages
   1) Pressure line filters are available in a full range of filter ratings.
   2) These filters provide direct protection to components downstream.

b) Disadvantage
   1) Because they are designed to be used at higher pressures, pressure line filter housings are usually heavier and higher in initial costs than return line filters of the same size.

12.4.5 Off-line filters

Off-line filters are located separate from the main system and generally contain their own pump for circulation. The advantages and disadvantages of using off-line filters are:

a) Advantages
   1) Differential pressure is not critical in the application of off-line filters.
   2) These filters are independent of the main circuit, therefore are not subject to transient conditions.
   3) These filters can run independently from the main circuit and so can continue to filter fluid in the reservoir.
   4) These filters are available in the full range of filter ratings.

   5) These filters can act as fill filters.

b) Disadvantages

   1) Off-line filters provide no direct protection for the components within the system; therefore, they are typically only used to supplement existing line filters.

   2) These filters are not able to filter 100 % of the fluid, so a proportion of the contaminant remains in the system.

   3) These filters cannot respond quickly to clean up ingression from sources such as the addition of new hydraulic fluid or rapid component wear or failure.

12.4.6 Reservoir filters

The importance of reservoir filters cannot be overemphasised as they offer an inexpensive and effective way to remove atmospheric particles instead of allowing them to enter the system, where they can cause wear and premature clogging of more expensive line-mounted filters. They come in the following forms:

a) Air breather filters — These remove airborne particles as air is exchanged between the interior and exterior of the reservoir. The rating of the filter is typically finer than the finest filter in the system so that it removes most of the particles that would be removed by the system filters. Its size is consistent with the local environmental conditions to give an acceptable service life.

   A common practice is to use discs of filter paper inserted into the cap of the filling access hole (so-called filler/breathers). While these might be adequate for use in clean environments, they are not recommended as the sole means of air breather filtration where higher contamination levels are experienced, as the small filter area can necessitate frequent replacement. In addition, their small size and lack of support means that they can clog quickly and, if not changed in time, are easily damaged by fatigue; as a result, all protection would be lost.

b) Fill filters — As their name suggests, these filters remove the particles contained in fluid used to replenish system fluid. Fill filters typically have a rating that is finer than the finest filter in the system so that they remove nearly all the particles from the new fluid. Reservoir-top return line filters sometimes serve as fill filters.

c) Desiccant air filters — If the system is in a humid environment and the reservoir allows for the ingress of air, then water vapour can be drawn in and contaminate the hydraulic fluid (see 4.3). This moisture can be removed using a desiccant material either on its own or incorporated into a particulate filter.

12.5 Filter sizing

Adequately size the filter for the intended application using both prior experience and filter manufacturer guidelines. An undersized filter can result in excessive differential pressures, premature bypass, unsatisfactory filter performance and inadequate service life.

Fluid flowing through a filter creates a differential pressure that is a function of the filter design, the fluid's flow rate and viscosity, and the contaminants collected on the filter. As contaminants continue to accumulate, this differential pressure increases until it exceeds the limits recommended by the manufacturer. Increasing the maximum allowable differential pressure does not provide an equivalent increase in service life. Once the differential pressure begins to rise, the rate of increase continually accelerates, which results in little difference either in capacity or in time to clogging.

For optimum performance, the filter is always sized in accordance with the filter supplier recommendations. Designers typically take into account surges in flow rates and temperature and pressure effects on fluid viscosity.

As a guideline, the following maximum clean element differential pressure values are recommended for various system locations:

a) suction lines — 3,4 kPa (34 mbar);

b) return lines — 30 kPa (0.3 bar); and

c) pressure lines — 100 kPa (1 bar).

However, these values ultimately depend on the relationship between the clean element differential pressure and the value of the setting of the differential pressure device and/or bypass valve. The ratio of the bypass valve setting (at the lower tolerance) divided by the clean element pressure drop (at the highest viscosity) is sometimes used to size filters. The following values can be used as guidelines:

a) A ratio greater than 10 is ideal and generally provides optimum filter life.

b) A ratio of 5-10 generally provides reasonable filter life.

c) A ratio less than 3 is likely to be problematic and lead to short filter life.

In poor operating environments that have a high concentration of dust suspended in the atmosphere, or where there are several exposed cylinders or other components that might allow ingressed contaminant, filters with greater retained capacity or effective filtration area are typically specified. Unfortunately, there is no proven method to calculate ingression rates, and even if there were, there is no direct relationship between filter retained capacity and actual filter service life; see 10.2.2 e). Therefore, sizing a filter for a desired service life is based more on previous experience than specific calculations. If the service life of the filter is not satisfactory, increase the amount of effective filtration area in proportion to the service life improvement required by increasing the filter size or adding additional filters.

12.6 Assessment of candidate filters

12.6.1 The system designer identifies the performance capability of candidate filters in similar applications. In doing so, the system designer does not use ratings alone, for reasons discussed earlier, and is advised to consult a filtration specialist in accordance with 12.6.2 through 12.6.5.

12.6.2 In cooperation with a filtration specialist, the system designer identifies several candidate filters that meet the parameters defined in 12.2.2 for further consideration.

12.6.3 Primary consideration is often given to filters already in use by the system designer’s company. This is commonly done to minimize the number of parts that need to be stocked and serviced.

12.6.4 When feasible, the system designer physically examines representative filters and obtains updated test data obtained under conditions that approximate the intended end use application.

12.6.5 At this point in the selection process, the system designer is aware of and relatively familiar with more than one potential filtration solution.

12.7 Verification of correct filter selection

For a new application, it is advisable to take the following steps to verify that the proper filters have been selected:

a) When feasible, a preproduction evaluation of the candidate filter(s) in an application that duplicates or simulates the intended end use as closely as possible is highly beneficial.

b) When a new filtration system is introduced into production, the performance of the filter is typically measured in service, both during the commissioning trials and when in service. If the filter is for control of wear-producing particles, the filter is expected to provide the RCL; if it does not, the filter can be changed for one of a different rating. For filters intended to protect a component, the performance of the component being protected can be observed through a field follow-up. The extent of this field follow-up depends on individual requirements, and, where applicable, on how the new system differs from those already in use.

c) To assure continued successful performance of a filtration system, the system designer typically clearly identifies the approved filter(s) by supplier name and part number. It is possible, however, that other filters might prove to be equally satisfactory.

13 Summary

While the selection and application of filters is not yet an exact science, a number of valid observations can be made:

a) As filtration requirements become more demanding, the system designer will be expected to become more knowledgeable about system contamination and its control.

b) The system designer needs to be aware that each millilitre of fluid that appears to be clean can contain thousands of potentially damaging microscopic particles. These contaminants can never be completely eliminated and, if they are left unattended, the small but irreversible damage they cause can go unnoticed for very long periods of time.

c) For each clearance in a component, there is a specific particle size, shape, and hardness which are most damaging in terms of abrasive wear. Because contaminants are continually ingressed into the system and are continually being re-sized within the system, it is probable that particles of this particular size are always present somewhere within the system.

d) Filters have proven to be an effective, low-cost means of reducing the amount of particulate contamination to a level consistent with the long-term durability objectives of the hydraulic system.

e) The most serious flaw in any filtration system is the presence of a fluid path that allow contaminants to continually bypass the filter element. Typical causes include: a tear in the filter medium, a malfunctioning bypass valve, an improper housing seal, or loss of filter element integrity.

f) The most critical periods for contaminant damage generally occur at the first construction of the system and immediately after a repair or other maintenance activity.

Annex A
(informative)

Types of filters and separators

A.1 Strainers

Strainers are coarse filters in which the filter medium consists of relatively coarse woven wire mesh or screen. Their main use is in reservoir filling points and in pump suction lines to protect the system from the ingress of relatively large debris without causing excessive differential pressure.

The restrictions placed on pump inlet filters means that they are generally coarse ($>$ 65 µm), so they only protect the pump against large contaminants rather than control the general level of contamination.

A.2 Fibrous media filters

Fibrous media filters are the most commonly used and most versatile type of hydraulic filters and can both control general contamination and protect components. The filter medium is constructed of small-diameter fibres of glass, cellulose, metal, or synthetic polymers arranged in a random matrix so that they present a tortuous path for flow through the medium. This improves efficiency of particle removal, strength and particle retention capacity. These filters come in a variety of ratings, from 3 µm(c) upwards, based on an ISO 16889 filtration ratio of 200. They can be manufactured to withstand a range of differential pressures without significant loss in performance, from low, e.g., 1 MPa (10 bar), to high, e.g., $>$ 21 MPa ($>$ 210 bar). They are usually disposable.

A.3 Last-chance filters

Last-chance filters are used solely for direct component protection and usually have ratings greater than 20 µm. They are fitted directly upstream of a component, either as a conventional cartridge element, as a disc or cone in the inlet connector of the component or as a cylinder for installation within the component. They can be made from a range of materials but are usually woven metallic mesh or sintered metal. Their contaminant capacity is severely limited by both size and materials, but some are designed to be cleaned and re-used.

A.4 Electrostatic separators

Electrostatic separators make use of an electrostatic charge to separate contaminants from the fluid and are capable of removing contaminants over a wide range of particle sizes and materials. They require very low fluid velocities to facilitate capture and retention of the particles and, although their efficiency of removal on a single-pass basis is low, their retention capacity is relatively high with little or no increase in differential pressure.

Electrostatic separators are only suitable for an off-line application, and so can be viewed as supplementary filters, as they do not afford direct contamination control or direct protection to components. Care needs to be taken when using them to clean up multiple systems, as they contain a significant volume of fluid (8 L to 100 L depending on size), which might not be compatible with the fluid in the system to which they are connected.

Electrostatic separators are typically operated continually, because switching them off removes the electrostatic charge on the particles, which could lead to substantial re-contamination of the system when the flow is reinstated.

Most electrostatic separators do not function with water-based fluids, fluids containing water or fluids with high conductivity.

A.5 Magnetic separators

Magnetic separators are designed to collect ferrous and charged particles, but their effectiveness is relative to the fluid velocity through the separator. As a result, their application is generally limited to return line applications. Magnetic separators play a useful role as a diagnostic tool in monitoring a system for wear failure.

A.6 Air breather filters

Air breather filters allow the exchange of air between a component and the atmosphere. The rating of the air breather filter needs to be finer than the finest filter on the system, so that it removes most of the ingressed contaminant; this can considerably extend the life of the other filters in the system. The rating of the filter medium in air breather filters are typically about eight times higher than a comparable filter for liquid because in air, an additional transport mechanism (Brownian motion) helps to increase the capture rate. The filter is typically large enough to prevent pressure build-up within the reservoir when the fluid level changes. An inadequately sized or partially blocked air breather filter can cause fatigue damage to the reservoir. Special care needs to be taken when systems operate in hostile environments and the size of the filter, and hence its contaminant capacity, needs to be increased accordingly.

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