HYDAC | FILTER SYSTEMS

Practical
Contamination
Management
From Processing
to Delivery

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1 Definition of Contamination Management

Contamination management pertains to the analysis and optimization of processes with regard to the cleanliness of components, systems and the purity of the fluids employed. In today's hydraulic systems — in the automotive industry and their suppliers, the hydraulics and mobile hydraulics industry — smaller, lighter and more powerful components are currently being employed as compared to say 10 years ago. The use of these components also means that the demands made of system cleanliness are now much higher, as has been shown by various studies.

Between 70-80 % of hydraulic system outages is due to increased contamination. This failure rate not only applies to the classic hydraulics industry. Contamination Management is also a key issue in the automotive industry, in which the use of electrohydraulic systems is on the rise. In this context, hydraulic or fluid power systems are used in a general sense for all industries (automotive, hydraulics and mobile hydraulics industries). Cleanliness specifications are currently applied in the automotive industry for the following:

- motors (fuel and oil supply systems)
- power steering
- manual/automatic transmissions
- electrohydraulic systems (suspension, clutch, brake, ABS and ESP systems)
- central hydraulic systems

This list is by no means exhaustive and is intended rather as a sample of the areas in which contamination management plays a role.

In the past, power fluid systems were equipped with system filtration which cleaned the system during commissioning and then had the task of maintaining system fluid cleanliness at a constant level, e.g. by using commissioning filters and initial brief maintenance intervals followed by changing over to system filtration. This approach frequently no longer suffices due to the growing demands made of today's hydraulic systems (extended maintenance intervals and mounting cost pressure). Precommissioning flushing is performed in large systems in the hydraulics industry to quickly bring the contamination level down to an acceptable level.

However, in small, mass-produced hydraulic systems (e.g. in the automotive and hydraulics industries) this is not always possible. That is why contamination management begins with the manufacture of the individual components and extends throughout the entire process chain up to and including the finished component. Ideally, the design and development departments are also integrated in this process so that component design facilitates the washing of components in a cost-efficient manner. Suppliers also have to be involved in contamination management when the manufacturing process involves a large portion of sourced components. By introducing contamination management with a view to minimizing particulate concentration in all areas, beginning with manufacturing and extending to the operation of the entire system, system malfunction and failure caused by particulate contamination can be prevented and, as a result, costs savings achieved. Cutting the costs of machining tools, improving the utilization of test stations, and optimizing the use of washing machines can do this.

This results in the following contamination management tasks:

- development of systems which are optimized so as to facilitate cleaning

- optimizing and monitoring washing and flushing processes

- training employees and raising their awareness

- detecting and eliminating sources of contamination

- drafting analysis instructions

- drafting cleanliness specifications for components and systems

An overall cost assessment is done to gauge the success of contamination management.

The following factors are considered:

- warranty and non-warranty courtesy work
- energy costs
- reworking costs
- machining tool costs
- operating costs of washing machines and test stations
- labor costs, etc.

The principles and applications of contamination management are detailed below.

Definitions:

Contamination management	monitoring/optimization of cleanliness in material flows and system assembly
Power fluid system	hydraulic systems, including automotive systems containing fluid fillings (e.g. motors, transmissions, power steering, ABS...)
Basic contamination	quantity of contamination present subsequent to assembly
Ingress contamination	particulate contamination caused by ingression
Initial damage	damage to surfaces caused during function testing/commissioning or assembly of systems
Contamination monitoring	analysis of processes with regard to the ingress of dirt caused by them
Online measurement process	measurement process in which the sample to be analyzed is fed to a measurement device directly from the system, e.g. automatic particle counter of a hydraulic system
Offline measurement process	measurement process in which the sample is taken from the system and analyzed elsewhere, e.g. taking an oil sample and sending it in to a laboratory

2.1 Definition of Contamination Types

Various types of contamination occur in power fluid systems: gaseous (e.g. air), liquid (e.g. water) and solid contaminants.
An overview of the various contamination types is shown in the following diagram:

Fig. 1: Contamination Types

```
                    Contamination types                              Affect


        Gaseous            Liquid           Soild


        Air                Water            Extremely hard particles        Extremely
                                            Corundum                        abrasive
                                            Scale
                                            Rust


                                            Hard particles                  Highly
                                            Iron                            abrasive
                                            Steel
                                            Brass
                                            Bronze
                                            Aluminum


                                            Soft particles                  Slightly
                                            Fibers                          damaging
                                            Gasket/seal abrasion particles
                                            Rubber particles
                                            Paint particles
```
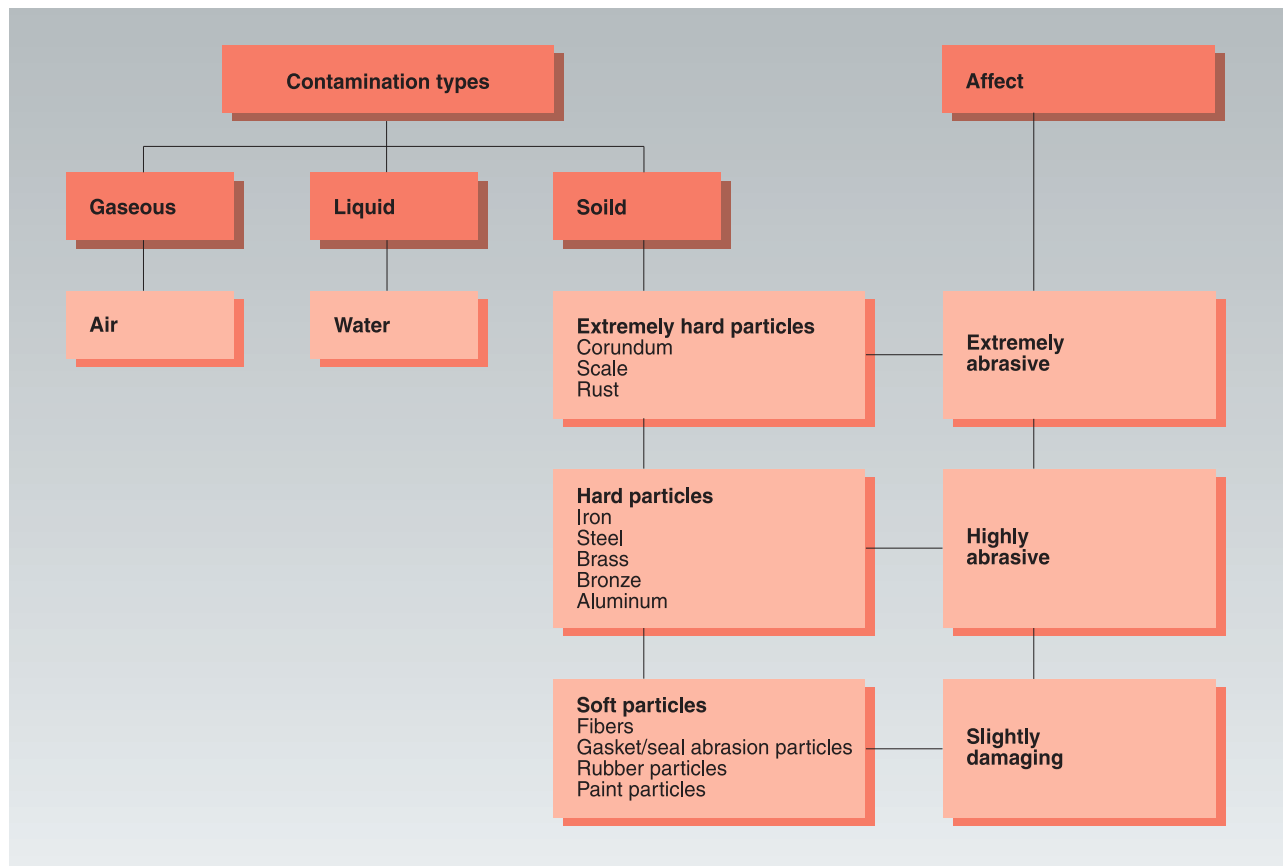
As you can tell from examining Figure 1, solid contamination is subdivided into three groups: extremely hard, hard and soft particles. Extremely hard particles can cause substantial damage in power fluid systems if they are not removed as quickly as possible. Preventive measures can reduce the ingress of contaminants in systems.

Hard particles are frequently listed separately in specifications. Maximum values are specified for the longest dimension these hard particles may have, e.g. largest abrasive particle:
max. 200 µm or 200 x 90 µm or no particles > 200 µm.

Not only the hardness of contamination particles play a role but also their number and size distribution as well.

The particle size distribution in new systems is different from that of systems that have been in operation for a number of hours.

In new systems, there is an accumulation of coarse contaminants up to several millimeters long, which are then increasingly reduced in size in the course of operation or eliminated by filtration. After several hours of operation most particles are so small that they are no longer visible to the naked eye.

When commissioning power fluid systems there is additional particulate contamination by virtue of abrasive wear in which rough edges are worn away through running-in. Contamination management can't prevent this ingress of contaminants, however if basic contamination is lower there is less abrasion during system startup.

Fig. 2

Cleaning of a Power Fluid System with and without Contamination Management
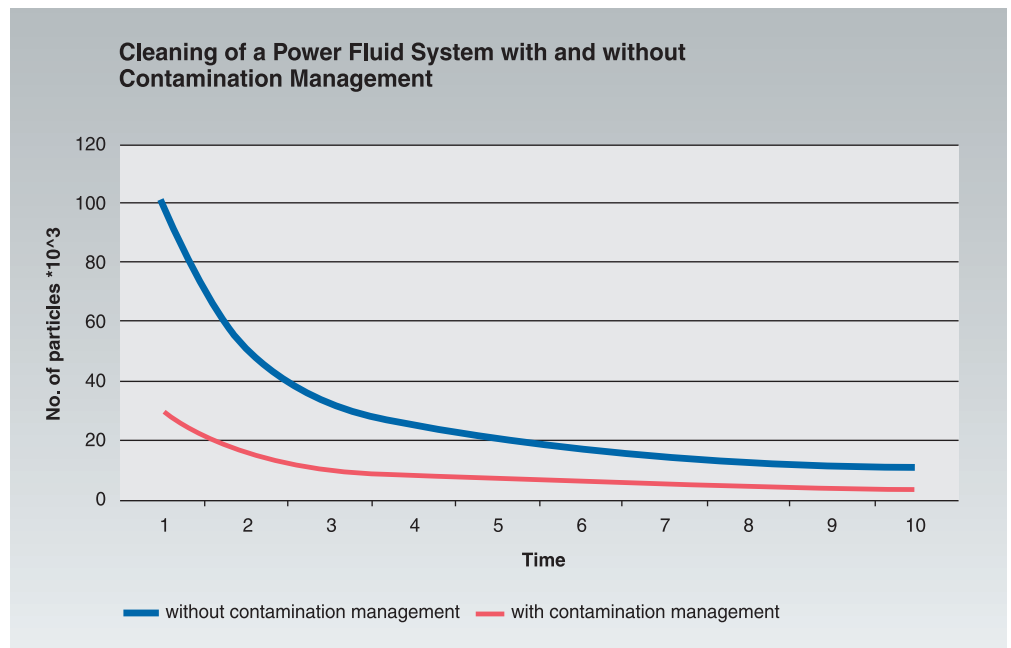
As the above diagram shows, the level of contamination without contamination management is higher throughout system operation as compared to a system in which contamination management is employed, the result being that more initial damage may be caused to surfaces.

The following microscope images show typical particle samples as occur in power fluid systems.

Fig. 3
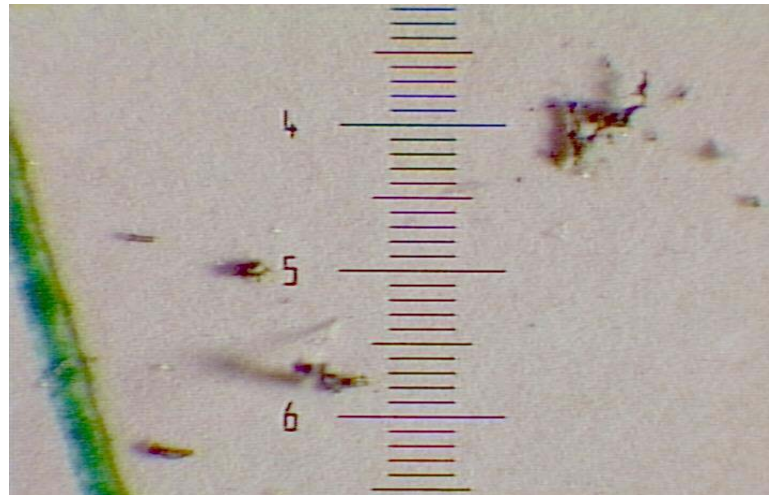
Sample containing coarse particles
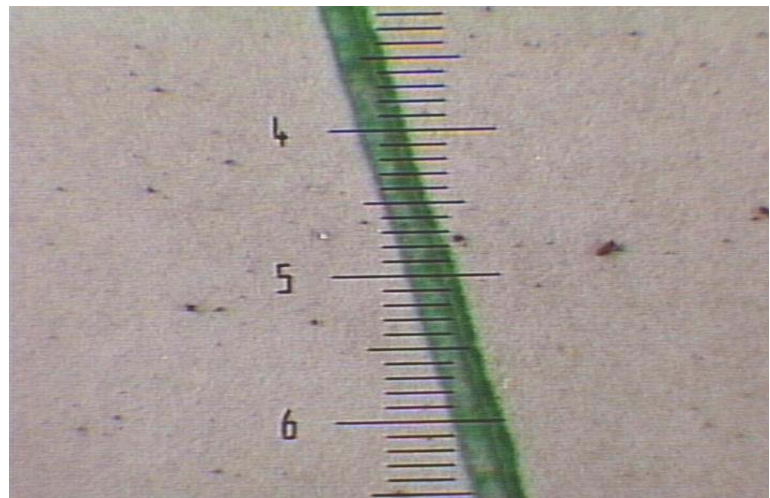
Sample containing fine particles

Fig. 4

An average healthy human eye can see items down to ca. 40 µm in size. Particle analyses are conducted using a microscope or in power fluid systems using particle counters employing the light extinction principle (cf. section 2.3.5).

2.2
Consequences of Particulate Contamination in Power Fluid Systems

Particulate contaminants circulating in power fluid systems cause surface degradation through general mechanical wear (abrasion, erosion, and surface fatigue).

This wear causes increasing numbers of particles to be formed, the result being that wear increases if the "chain reaction of wear" is not properly contained (by 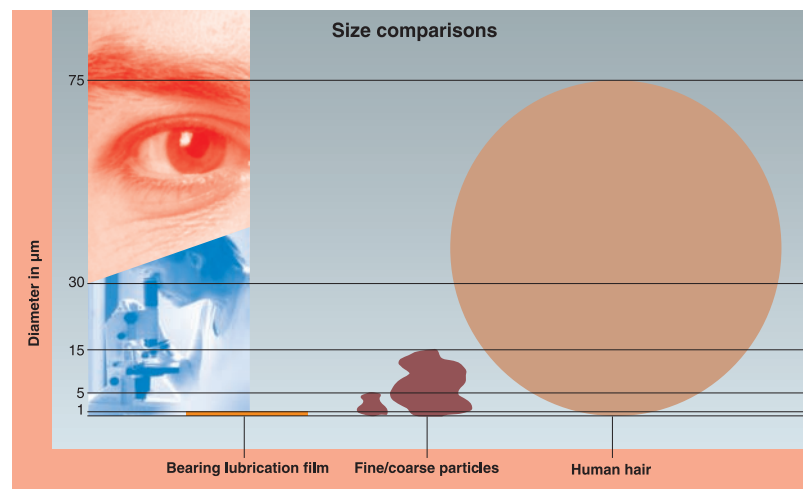reducing contamination). Gaps grow larger, leakage oil flows increase in size, and operating efficiency (e.g. of pumps) decreases. Metering edges are worn away, thus resulting in control inaccuracies. In some cases, blockage of control ducts or nozzle bores occurs.

The chain reaction of wear during the everyday operation of hydraulic systems has to be interrupted by properly designed and dimensioned filter systems. However, the measure of security afforded the user is deceptive as highly damaging contaminants seep in during component and system assembly and system installation. This ingress of contaminants not only can cause preliminary damage to system components but also premature failure as well.

Fig. 5
Examples of Wear
to Movable Surfaces

Radial clearance of the piston ring

High pressure

Low pressure

Valve seat
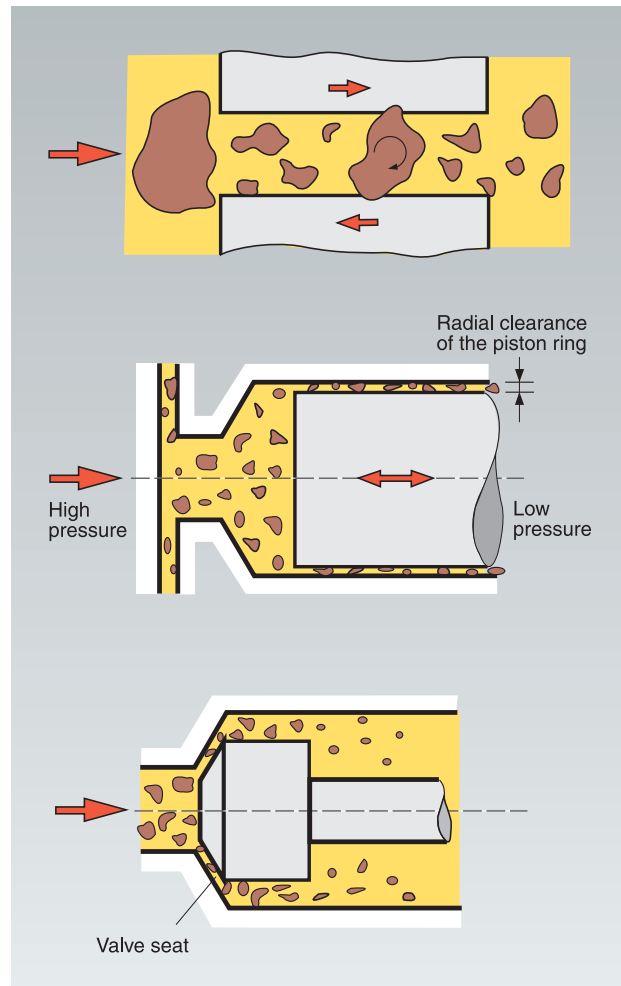
Generally speaking, system filtration concepts are not designed to adequately deal with large quantities of dirt as occur in connection with:
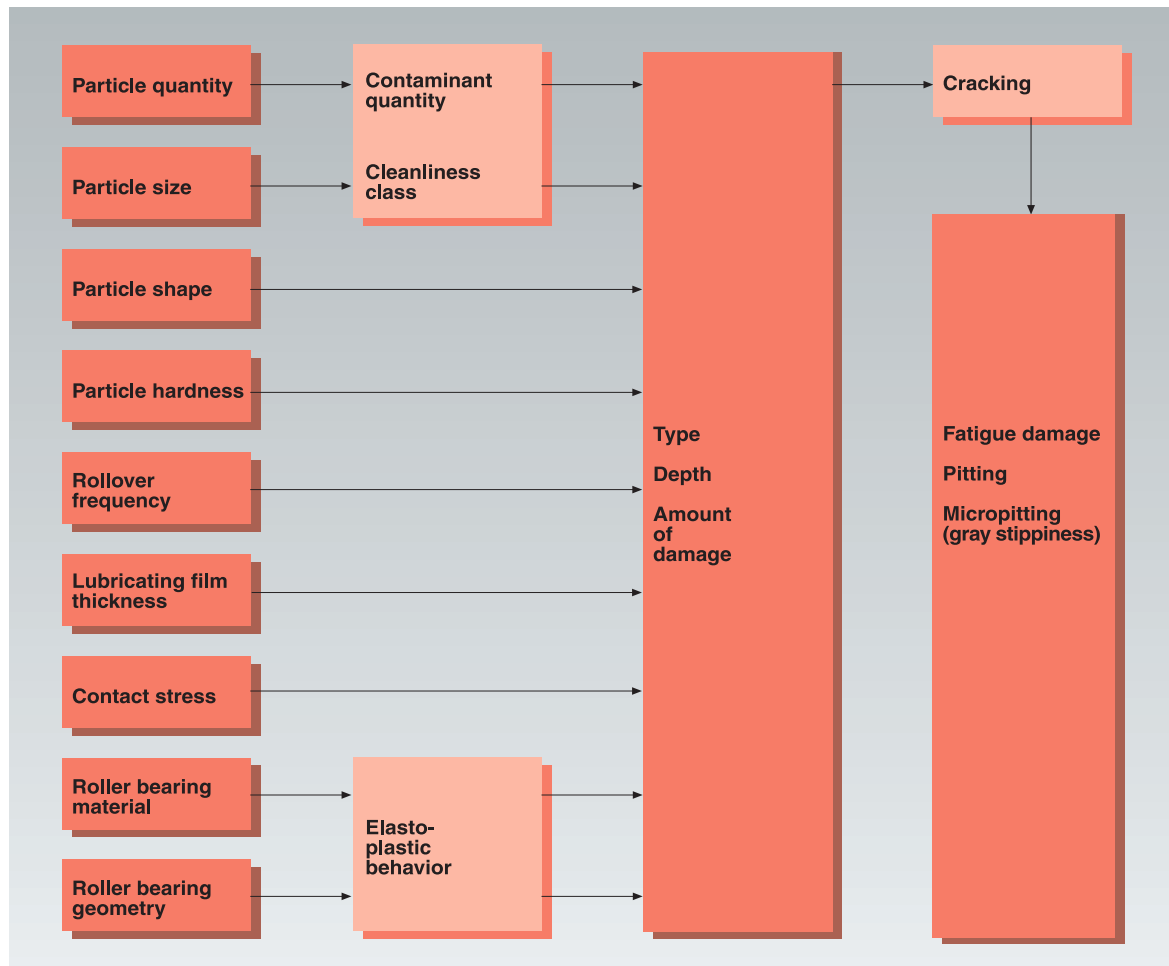
component machining

system assembly

system filling

commissioning

system repair work

A study conducted by the University of Hanover describes the factors impacting the fatigue life of roller bearings as follows:

"The quantity of contamination in the lubricant is described by the particle quantity and size. Combining this with particle hardness and geometry results in the type and extent of damage to raceways, with the extent also being affected by the elasto-plastic behavior of the material. The amount of damage is determined by the quantity of particles in the lubrication gap and the rollover frequency. Continued rollover leads to cracking, which in the form of fatigue damage (pitting) leads to roller bearing damage (bearing failure)."

In practice ball bearings with their punctiform contact are shown in most cases to be less sensitive to particulate contamination than roller bearings with their linear contact. Friction bearings with their larger lubrication gaps are the least sensitive to particulate contamination.

Fig. 6
Factors Affecting
Roller Bearing Life (1)

Particle quantity	Contaminant quantity		Cracking
Particle size	Cleanliness class		
Particle shape			
Particle hardness		Type	Fatigue damage
Rollover frequency		Depth	Pitting
Lubricating film thickness		Amount of damage	Micropitting (gray stippiness)
Contact stress			
Roller bearing material	Elasto-plastic behavior		
Roller bearing geometry			

The following table provides an overview of the most common gap sizes:

Fig. 7
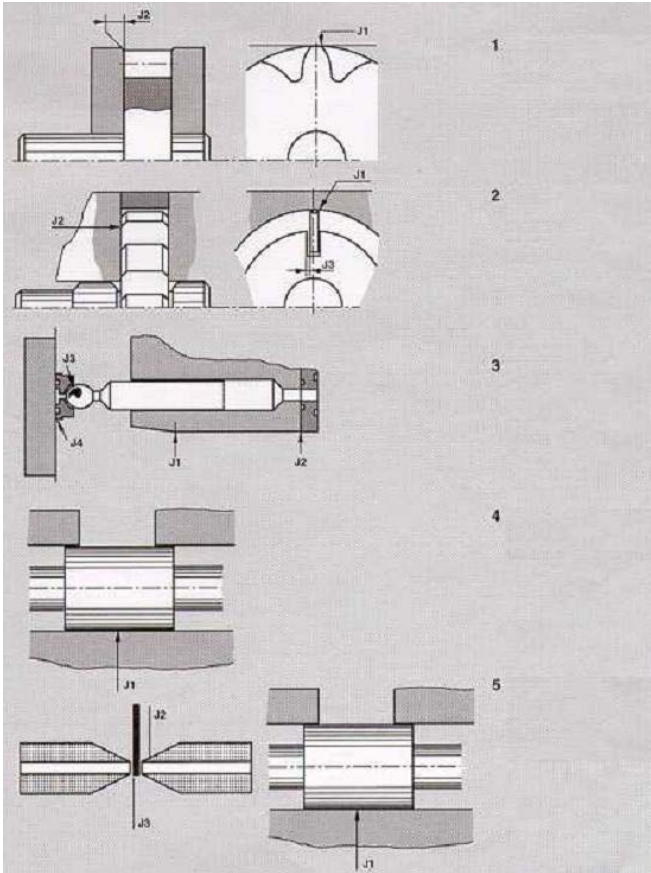
Component	Typical critical clearance [μm]
Gear pump (J1, J2)	0.5 – 5
Vane-cell pump (J1)	0.5 – 5
Piston pump (J2)	0.5 – 1
Control valve (J1)	5 - 25
Servo valve (J1)	5 – 8

Comprehensive studies of particle distributions on components and in hydraulic systems have shown that at the beginning of a system's life, i.e. during assembly and commissioning, the particles are larger than during subsequent operation.

These large particles – up to several millimeters in size in part – can cause spontaneous outages:

 valve blockages

 substantial preliminary damage to pumps

 destruction of seals and gaskets followed by leakage

Active contamination management enables this rate can be reduced and costs accordingly cut, i.e.

 costs caused by production stops

 costs caused by delays in commissioning systems

 costs incurred by longer testing periods since a flushing cycle is required to remove integral contamination

 warranty costs

 reworking costs

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Fig. 8
Destroyed Raceway of
a Ball Bearing Caused by
Particulate Contamination

Fig. 9
Chip Embedded in the Surface
of a Friction Bearing

Contamination management
counters the situation as follows:

In new systems the individual
components are brought to a
uniform cleanliness level, the filling
fluid is kept at a defined level, as is
the fluid during system operation
(cf. Contamination Monitoring,
section 5 ff.).

2.3
Classification of Particulate Contamination in Fluids

The objective of the procedures described below is to enable a reproducible classification of particulate contaminants in fluids.

Currently there are 4 procedures for classifying particulate contaminants in fluids:

Standard	ISO 4405	ISO 4406:1999	NAS 1638	SAE AS 4059
Application	Highly contaminated media, e.g. washing media, machining fluids	Hydraulic fluids Lubrication oils	Hydraulic fluids Lubrication oils	Hydraulic fluids Lubrication oils
Parameters	[mg/liters of fluid]	Number of particles > 4 µm (c) > 6 µm (c) > 14 µm (c)	Number of particles 5 – 15 µm 15 – 25 µm 25 – 50 µm 50 – 100 µm > 100 µm	Number of particles > 4 µm (c) > 6 µm (c) > 14 µm (c) > 21 µm (c) > 38 µm (c) > 70 µm (c)
Analysis methods	In this lab method, 1 liter of the fluid undergoing analysis is filtered through a prepared membrane, which is then weighed	**1. Manual evaluation:** The fluid undergoing analysis is filtered through a prepared membrane and the cleanliness class (contamination rating) estimated or counted by hand using a microscope. **2. Automated particle counting:** The fluid undergoing analysis is conducted through a particle counter, which tallies the particle fractions.		
Remarks	Very time-consuming method	**1. Manual evaluation:** Very time-consuming, not very exact. **2. Automated particle counting:** Result available almost immediately.		

These standards are described in detail below.

2.3.1
ISO 4405 – "Hydraulic Power Fluid – Fluid Contamination – Determining Particulate Contamination Employing Gravimetric Analysis Methods"

This international standard describes the gravimetric method for determining the particulate contamination of hydraulic fluids.

Basic principle:

A known volume of fluid is filtered through one or two filter disks using vacuum action and the weight differential of the filter disks (upstream and downstream of filtration) measured. The second membrane is used for evaluating accuracy.

In order to determine the gravimetric contamination of the fluid, a representative sample has to be taken from the system. ISO 4405 describes the cleaning procedure for the equipment being used. It also describes the preparatory procedures for the analysis membranes:

The membranes are flushed with isopropanol prior to use, dried in a drying oven until they achieve a constant weight, and then cooled in a defined dry environment. It is important that cooling takes place in a defined dry environment, otherwise the membrane absorbs moisture from the surroundings, thus skewing the final result.

Fig. 10

Afterwards the membrane is weighed and this value recorded as m (T).

Now the membranes are fixed in the membrane retainer and the fluid undergoing analysis is filtered. This is followed by flushing off the contaminant on the membrane using filtered solvent to completely remove the contaminant. When analyzing oil-laden fluids it is important that the remaining oil is completely flushed off the membrane.

This is followed by drying the membrane, cooling and weighing it (as described above). The measured value is now recorded as m (E).

Gravimetric contamination is calculated as follows:

$$M (G) = m(E) - m(T)$$

2.3.2
ISO 4406:1999

In ISO 4406, particle counts are determined cumulatively, i.e. > 4 µm (c), > 6 µm (c) and > 14 µm (c) (manually by filtering the fluid through an analysis membrane or automatically using particle counters) and allocated to measurement references.

The goal of allocating particle counts to references is to facilitate the assessment of fluid cleanliness ratings.

In 1999 the "old" ISO 4406 was revised and the size ranges of the particle sizes undergoing analysis redefined. The counting method and calibration were also changed.

This is important for the user in his everyday work:

Even though the measurement references of the particles undergoing analysis have changed, the cleanliness code will change only in individual cases. When drafting the "new" ISO 4406 it was ensured that not all the existing cleanliness provisions for systems had to be changed (Lit. © HYDAC, "Filters – Power Fluid Technology, New Test Dust, New Calibration, New Filter Testing Methods — How This Impacts Everyday Work").

1,300 – 2,500 particles > 4 µm (c)
160 – 320 particles > 6 µm (c)
10 –   20 particles > 14 µm (c)

Overview of the changes:

	"old" ISO 4406:1987	"new" ISO 4406:1999	
Size ranges	> 5 µm, > 15 µm		> 4 µm (c) > 6 µm (c) > 14 µm (c)
Dimension determined	Longest dimension of a particle		Diameter of the area-equivalent circle ISO 11171:1999
Test dust	ACFTD dust	1-10 µm Ultrafine fraction	ISO 12103-1A1
		SAE Fine, AC Fine	ISO 12103-1A2
		SAE 5-80 µm ISO MTD Calibration dust for particle counters	ISO 12103-1A3
		SAE Coarse Coarse fraction	ISO 12103-1A4
Comparable size ranges	Old ACFTD calibration	Comparable ACFTD dusts	New NIST calibration

		< 1 µm
		  4.3 µm
		  15.5 µm
			4 µm (c)
			6 µm (c)
			14 µm (c)

Allocation of particle counts to cleanliness classes:

No. of particles/ml		Cleanliness class
Over	Up to	
2,500,000		> 28
1,300,000	2,500,000	28
640,000	1,300,000	27
320,000	640,000	26
160,000	320,000	25
80,000	160,000	24
40,000	80,000	23
20,000	40,000	22
10,000	20,000	21
5,000	10,000	20
2,500	5,000	19
1,300	**2,500**	**18**
640	1,300	17
320	640	16
160	**320**	**15**
80	160	14
40	80	13
20	40	12
10	**20**	**11**
5	10	10
2.5	5	9
1.3	2.5	8

The reproducibility of the results in cleanliness class 8 depends on the concentration of particles in the sample undergoing analysis.

If the number of particles counted in the sample is larger than 20, the result has to be reported with ≥.

Note: increasing the measurement reference by 1 causes the particle count to double.

Example:
ISO class 18 / 15 / 11 says that the following are found in 1 ml of analyzed sample:

1,300 – 2,500 particles > 4 µm (c)
160 – 320 particles > 6 µm (c)
10 –   20 particles > 14 µm (c)

Fig. 11
Microscopic Examination of an Oil Sample (100 ml)
Magnification 100x (ISO 18 / 15 / 11)
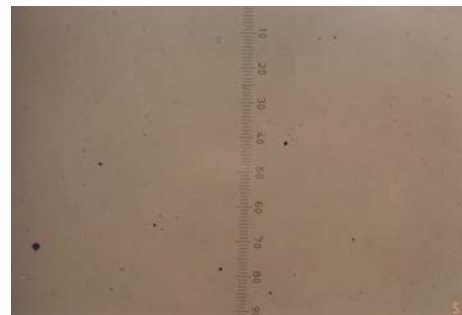
2.3.3
NAS 1638

Like ISO 4406, NAS 1638 describes particle concentrations in liquids. The analysis methods can be applied in the same manner as ISO 4406:1987.

In contrast to ISO 4406, certain particle ranges are counted in NAS 1638 and attributed to measurement references.

The following table shows the cleanliness classes in relation to the particle concentration analyzed:

		Particle size [μm]				
		5-15	15-25	25-50	50-100	>100
		No. of particles in 100 ml sample				
	00	125	22	4	1	0
	0	250	44	8	2	0
	1	500	89	16	3	1
	2	1,000	178	32	6	1
	3	2,000	356	63	11	2
	4	4,000	712	126	22	4
Cleanliness class	5	8,000	1,425	253	45	8
	6	16,000	1,850	506	90	16
	7	32,000	5,700	1,012	180	32
	8	64,000	11,600	2,025	360	64
	9	128,000	22,800	4,050	720	128
	10	**256,000**	**45,600**	**8,100**	**1,440**	**256**
	11	512,000	91,200	16,200	2,880	512
	12	1,024, 000	182,400	32,400	5,760	1,024

Increasing the class by 1 causes the particle count to double on average.

The particle counts of class 10 are bold-faced in the above table.

Fig. 12
Microscopic Examination of an Oil Sample (100 ml)
Magnification 100x (NAS 10)
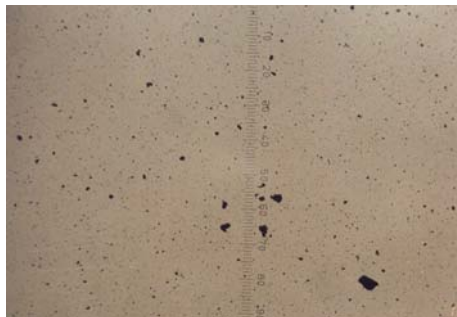
2.3.4
SAE AS 4059

Like ISO 4406 and NAS 1638, SAE AS 4059 describes particle concentrations in liquids. The analysis methods can be applied in the same manner as ISO 4406:1999 and NAS 1638.

The SAE cleanliness classes are based on particle size, number and distribution. Just like for the ISO classification, the different particle concentrations are assigned numerical codes (see table). Compared to the 3-digit ISO code, in which the particle size ranges are fixed (> 4 $\mu m_{(c)}$ / > 6 $\mu m_{(c)}$ / >14$\mu m_{(c)}$), the SAE cleanliness class assigns the capital letters A-F to the particle size range being considered.
These letters correspond to
> 4 $\mu m_{(c)}$ ... > 70 $\mu m_{(c)}$.

The following table shows the cleanliness classes in relation to the particle concentration determined:

The SAE cleanliness classes can be represented as follows:

1. Absolute particle count larger than a defined particle size

Example:

Cleanliness class according to AS 4059:6

The maximum permissible particle count in the individual size ranges is shown in the table in boldface.

Cleanliness class according to AS 4059:6 B

Size B particles may not exceed the maximum number indicated for class 6.

6 B = max. 19,500 particles of a size of 5 μm or 6 μm (c)

Maximum Particle Concentration [particles/100 ml]

Size ISO 4402 Calibration or visual counting*	> 1 µm	> 5 µm	> 15 µm	> 25 µm	> 50 µm	> 100 µm
Size ISO 11171, Calibration or electron microscope**	> 4 µm (c)	> 6 µm (c)	> 14 µm (c)	> 21 µm (c)	> 38 µm (c)	> 70 µm (c)
Size coding	**A**	**B**	**C**	**D**	**E**	**F**
000	195	76	14	3	1	0
00	390	152	27	5	1	0
0	780	304	54	10	2	0
1	1,560	609	109	20	4	1
2	3,120	1,220	217	39	7	1
3	6,250	2,430	432	76	13	2
4	12,500	4,860	864	152	26	4
5	25,000	9,730	1,730	306	53	8
6	**50,000**	**19,500**	**3,460**	**612**	**106**	**16**
7	100,000	38,900	6,920	1,220	212	32
8	200,000	77,900	13,900	2,450	424	64
9	400,000	156,000	27,700	4,900	848	128
10	800,000	311,000	55,400	9,800	1,700	256
11	1,600,000	623,000	111,000	19,600	3,390	1,020
12	3,200,000	1,250,000	222,000	39,200	6,780	

** Particle sizes determined according to the diameter of the projected area-equivalent circle.

* Particle sizes measured according to the longest dimension.

2. Specifying a cleanliness class for each particle size

Example:

Cleanliness class according to AS 4059: 7 B / 6 C / 5 D

Size B (5 µm or 6 µm (c)):
38,900 particles / 100 ml
Size C (15 µm or 14 µm (c)):
3,460 particles / 100 ml
Size D (25 µm or 21 µm (c)):
306 particles / 100 ml

3. Specifying the highest cleanliness class measured

Example:

Cleanliness class according to AS 4059:6 B – F

The 6 B – F specification requires a particle count in size ranges B – F. The respective particle concentration of cleanliness class 6 may not be exceeded in any of these ranges.

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2.3.5
Procedure in Evaluating Fluid Samples According to ISO 4406:1999, NAS 1638 and SAE AS 4059

A representative sample is taken of the fluid and analyzed as follows:

1. Manual procedure according to ISO 4407 (Hydraulic fluid power – Fluid contamination – Determination of particulate contamination by the counting method using a microscope).

ISO 4407 contains a description of a microscopic counting method for membranes. 100 ml of the sample undergoing analysis is filtered through an analysis membrane featuring an average pore size of < 1-µm and square markings. The standard also describes the cleaning procedure and maximum particle count of the negative control.

After the analysis membranes are dried, 10, 20 or 50 squares are counted depending on the size of the particles, followed by adding the values and extrapolating to the membrane diameter.

The manual count of the particles is done in the "old" levels of > 5 µm and > 15 µm since the longest dimension of a particle is counted in ISO 4407 yet the diameter of the area-equivalent circle is counted in the "new" ISO 4406:1999. As described above, the reference values obtained for this count correspond to the reference values of the "new" evaluation.

Fig. 13
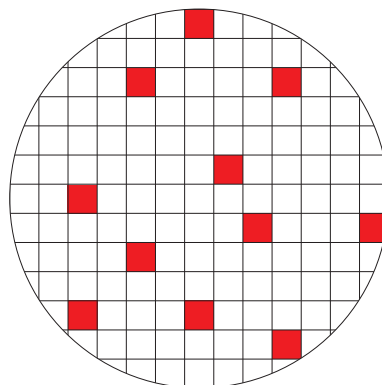
This counting method can only be used for very clean samples. Generally speaking, the cleanliness classes are estimated on the basis of reference photographs or the samples automatically counted.

2. Automated particle counting

Below follows a description of how common particle counters employing the light extinction principle function.

The figure below shows a simplified rendering of the measurement principle employed in the light extinction principle. The light source transmits the monochromatic light through the oil flow onto a photodetector, which generates a specific electrical signal. A shadow is created on the photodetector if a particle (black) comes between the light source and the photodetector.
This shadow causes the electrical signal generated by the sensor to change. This change can be used to determine the size of the shadow cast by this particle and thus the particle size to be determined.

Fig. 14
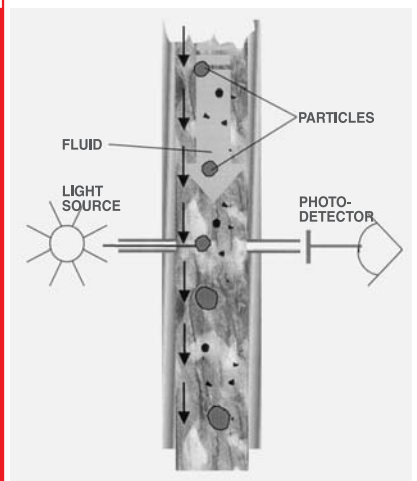
This procedure enables the cleanliness classes according to ISO 4406:1987, ISO 4406:1999, NAS 1638 and SAE AS 4059 to be determined.

The "noise" involved in this measurement principle is extraneous liquids and gases which cause the light beam to be interrupted and thus be counted as particles.

The particle counter should be calibrated according to ISO 11943 (for ISO 4406:1999).

The following types of automatic particle counting are used:

Online processes in which the sample is taken directly from the system and conducted into the particle counter, or the sensor is integrated directly in the system.

Fig. 15

Online Particle Counter of the FCU 2000 Series

Or offline processes in which the sample is filled into a sample container from which the liquid is conveyed through a particle counter.

Fig. 16

Laboratory Particle Counter with a Bottle Sampling Unit

BSU 8000 with FCU 8000

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3 Determining the Residual Dirt Quantity of Components

Determining the residual dirt quantities present on components can be done employing quantitative and qualitative factors.

Quantitative:
- mg/component
- mg/surface unit (oil-wetted surface)
- mg/kg component weight
  no. of particles > x µm/component
- no. of particles > x µm/surface unit (oil-wetted surface)

Qualitative:
length of the largest particle (subdivision into hard/soft)

Components with easily accessible surfaces are components in which only the outer surface is of interest for the most part when performing residual dirt analyses. There are exceptions here, e.g. transmission and pump housings, as the internal surface is of interest. These components belong to group 1 and their surfaces are not easily accessible in most cases.

Components in which the inner surfaces are examined or preassembled assemblies belong to group 2; for the analysis procedure for this group, refer to section 4.

There are two methods that can be used to determine the residual dirt of group 1 components:

3.1 Ultrasonic Method

The ultrasound method involves submitting the components to an ultrasonic bath, exposing them for a defined period of time at a defined ultrasonic setting and bath temperature. The particulate contamination is loosened by the exposure and then flushed off the component using a suitable liquid.

The particle dispersion in the flushing liquid obtained in this manner is analyzed according to specified evaluation methods (cf. section 3.4).

The ultrasonic energy setting and the duration of exposure have to be indicated in reporting the result. The ultrasonic procedure is particularly suitable for small components in which all surfaces have to be examined. Cast components and elastomers should not be subjected to ultrasonic washing if possible as a risk is posed here of the carbon inclusions in the cast piece being dissolved, thus skewing the results. These effects have to be ascertained prior to performing an ultrasonic analysis.

3.2
Flushing Method

Components with easily accessible surfaces or components in which only surface parts have to be examined are analyzed using the flushing method. This method involves flushing the surface undergoing analysis in a defined clean environment using an analysis fluid, which also has a defined cleanliness. A "negative control" or basic contamination control is performed prior to analysis in which all the surfaces of the environment, e.g. the collecting basin, are flushed and the value obtained reported as the basic contamination of the analysis equipment. The flushing fluid is then analyzed using the specified evaluation methods.

Fig. 17

Clean air area
Gun
Collecting basin
System filter
Ventilation and shut-off valve
Membrane retainer
Shut-off valve
Vacuum pump
Storage tanks
Compressed air port
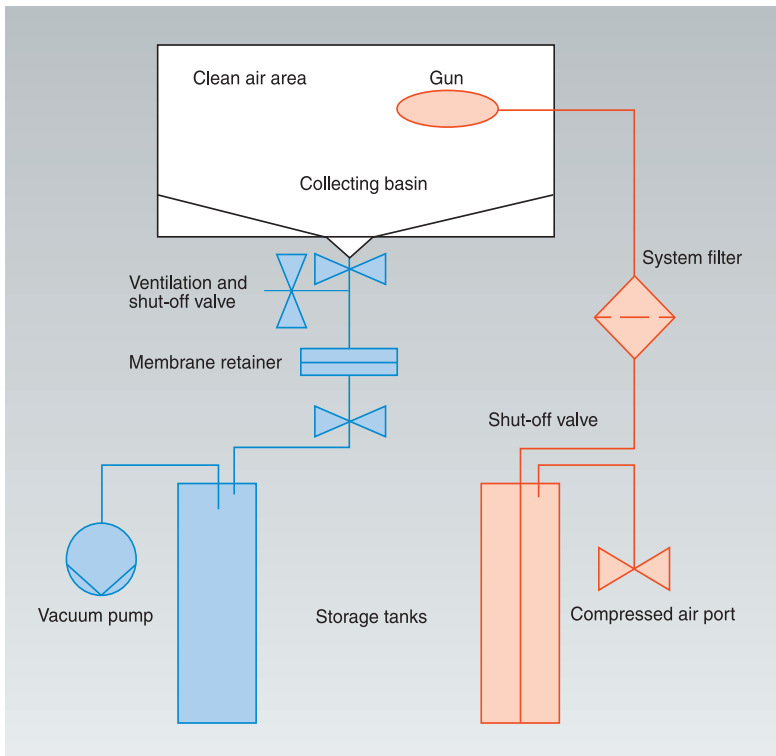
The areas shown in **red** are the flushing areas; those shown in **blue** the designated analysis area. In reality these two circuits are configured using suitable valves in such a manner that switchover can be done between the two storage tanks. The figure represents a simplified circuit diagram.

The analysis fluid is subjected to a pressure of ca. 4-6 bars and thus conveyed through the system filter and the spray gun into the analysis chamber. The system filter ensures that the analysis fluid sprayed on the surface being examined has a defined cleanliness. The particle-loaded fluid collects in the collecting basin and is filtered through the analysis membrane via vacuum action. The membrane is then evaluated according to the analysis methods described below.

3.3
Shaking Method

This method is very rarely used, as it is very difficult to reproduce manually. However, results are reproducible when automatic shakers such as those used in chemical laboratories are employed. The analyzed components are components subject to wear whose inner surfaces are to be analyzed (e.g. pipes, tanks). The important thing is that the particles are flushed out of the inside of the components after being shaken.

The following table shows a comparison of the various methods for analyzing components and assemblies.

	Flushing method	Ultrasonic method
How performed	Components are flushed with the analysis fluid in a defined clean environment.	Components are exposed to an ultrasonic bath and are then flushed with the analysis fluid.
Applications	Components in which only surface parts have to be examined and components in which ultrasound may damage the surfaces. Components with a simple design and with easily accessible surfaces.	Small components and components in which all surfaces are to be analyzed (the component size depends on the ultrasonic bath).
Pros	Analysis can be performed quickly	Reproducibility
Cons	Reproducibility Standards are not yet available (currently in preparation)	Analysis takes a long time The energy acts on the surface undergoing analysis The surface has to be flushed No valid standards

3.4
Evaluation Methods

Evaluating particle-laden flushing fluids can be done according to various criteria. Gravimetric analysis is useful for heavily contaminated components, whereas particle counts in various size ranges are useful for very clean components.

The following table provides an overview of the individual evaluation methods:

	Manual methods		Automated methods	
	Gravimetric method [mg/m2]	**Counting of particles on the analysis membrane [no. of particles > x µm/m2]***	**Counting of particles on the analysis membrane [no. of particles > x µm/m2]***	**Counting of particles in the fluid [no. of particles > x µm/m2]***
How performed	The particle-laden fluid is filtered through a prepared analysis membrane.			The particles in the particle-laden fluid are counted using an automatic particle counter.
	The analysis membrane is weighed before and after analysis and the gravimetry computed on the basis of the difference between the measured values.	The number of particles in the individual size ranges are estimated or counted. < 100 µm estimated > 100 µm counted	The analysis membrane is placed under a microscope and evaluated using a software tool. This software records the light-dark contrasts on the membrane and interprets them as particles.	
Applications	Samples exhibiting contamination > 10 mg	Samples featuring high a content of coarse contamination. Often combined with gravimetric evaluation.	Samples featuring a low contamination content < 5 mg.	Preferred for very clean components. When high dirt content is involved, the sample has to be diluted in order to perform counting.
Standard	ISO 4405	ISO 4407		ISO 11500
Advantages	Material types can also be analyzed. An overview can be quickly obtained of the largest particles. Air and extraneous liquids do not pose a problem (as long as no deposits form on the membrane).			Analysis can be performed quickly, can be integrated in process chain as on-line method, detection of small quantities of particles possible, measurement range selectable (2-400 µm). Accurate measurement method.
	Can be used for large particle quantities			
Disadvantages	Takes a long time (min. 1 h)	Takes a long time No. of particles < 100 µm estimated	Depending on the analysis accuracy this method can take a very long time. Light particles are not interpreted. Light-dark contrast is manually selected in most cases. The diameter of the area-equivalent circle is measured (=> result is not identical to visual appearance).	The sample has to be prepared (e.g. the sample might have to be diluted). Generally speaking, this is a statistical method providing for sufficient accuracy.
	Lab method	Lab method		
Application	Lab method Used as a control for indirect measurement techniques (e.g. off-line process control in test stations).		Lab method	On-line process control in manufacturing and assembly. Can also be used in labs.

* Alternative: also no. of particles / kg component weight

The following table provides an overview of applications of the analysis and evaluation methods:

Evaluation Analysis method			Gravimetry		Particle counting		
			Flushing	Ultrasonic method	Flushing	Ultrasonic method	Function testing*
Simple components	e.g.	easy-to-access surfaces gears	U	U	U	U	NU
Components	e.g.	internal surfaces pipes, tanks	U	NU	U	NU	CU**
Complex components	e.g.	Components featuring various bore holes or ducts control plates	CU**	NU	CU**	NU	U
Simple systems	e.g.	surface is to be analyzed immersed sensors	U	U	U	U	NU
Systems	e.g.	internal surfaces rails of common rail systems	CU**	NU	CU**	NU	U
Complex systems	e.g.	valves, pumps	CU**	NU	CU**	NU	U

  U = usable
CU = conditionally usable
NU = not usable
  * = section 4, Analysis of the Cleanliness of Systems on the Flushing/Test Stand.
** = It has to be ensured that the particles dislodged from the component can be flushed away.

4 Analysis of the Cleanliness of Systems on the Flushing/Test Stand

The cleanliness of components and systems that pass through a flushing or test stand can be determined on the basis of the cleanliness of the test fluid in some cases. This indirect analysis method is preceded by manual analyses for validation purposes.

For example, hoses are flushed by hand and the results evaluated in accordance with the methods discussed in section 3. At the same time, the cleanliness of the test fluid of the test stand is determined in the return flow, i.e. downstream of the component.

If a correlation is detected between the manual and the automatic (indirect) value, this means that indirect value analysis can be selected as a measure of quality.

The flushing stand used for analyzing the residual dirt content of systems has to feature the following:

1. Flushing has to be done using as turbulent a flow as possible.

2. The fluid used has to posses a dispersion effect.

3. All channels and surfaces have to be exposed to the flow.

4. The effectiveness of flushing can be improved by pulsating the flushing.

4.1 Turbulent Flow

Reynolds Number

The Reynolds number — a dimensionless reference — describes the flow properties of fluids. Below follows a brief description of how the Reynolds number is derived using pipe flow as an example.

Weights are discounted in the calculation of the Reynolds number. Generally speaking, only pressure, friction and inertial forces affect fluid elements and bodies subjected to flows. They have to be in balance at all points of the flow. If the relationship of friction and inertial forces is the same in similar points P1 and P2, then similar flows are said to be present.

Fig. 18
Similar Flows
Around Different Cylinders
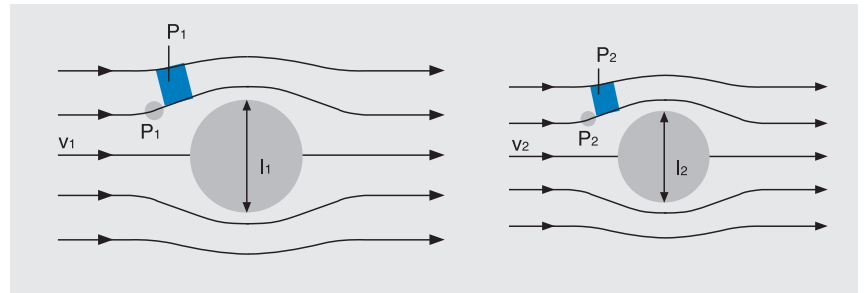
The Reynolds equation looks like this when the above properties are taken into account:

$$\textbf{Re} = \frac{\textbf{mean velocity * internal pipe diameter}}{\textbf{kinematic viscosity}}$$

$$\textbf{Re} = 21220* \frac{\textbf{Q}}{\textbf{di * v}} \quad \textbf{applies to pipelines and hoses}$$

Whereby: Q = volumetric flow rate (l/min)
v = viscosity (mm²/s)
and
d = inside pipe diameter (mm)

The critical Reynolds number Re_{crit} depends on kinematic velocity v, flow rate Q of the fluid, and the geometry of the passage through the flow is being conducted. If the Reynolds number of a flow is smaller than Re_{crit}, the flow is said to be **laminar**. **Turbulent** flow is said to be present for values above Re_{crit}. The critical Reynolds number for oil is given below.
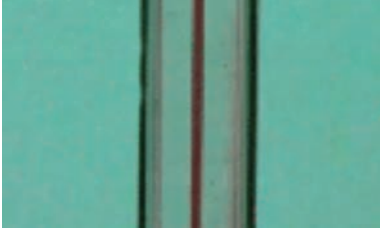
Re crit oil = 1900 – 3000

(Source: Kahrs, M.: Der Druckverlust in Rohrleitungen ölhydraulischer Antriebe; VDI Forschungsheft 537, Düsseldorf 1970)

The following diagrams show the difference between laminar and turbulent flow.
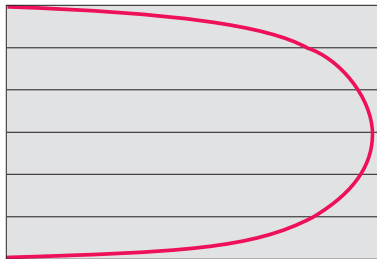
Fig. 19

Laminar Flow

All particles move without mixing.

The path of a particle is described by a stream thread.
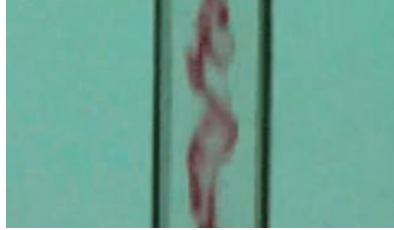
Parabola-shaped velocity distribution (applies to pipes).

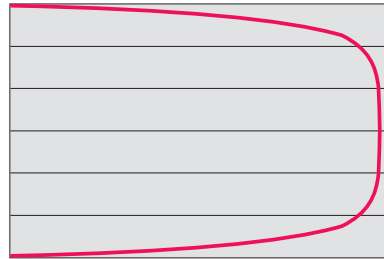

Reynolds number smaller than Re_{crit}

Turbulent Flow

All particles are continuously mixed.

The path of a particle cannot be predicted.

Relatively even time-averaged velocity distribution (flattened parabola).

Reynolds number larger than Re_{crit}

The above diagram shows a parabolic, **laminar flow** in a pipe. This shows that the flow velocity of a laminar current in the middle of the pipe (peak of the parabola) is larger than along the pipe wall.

In a **turbulent flow** this parabola flattens and spreads (when mean values are considered), as transversal currents are involved in a turbulent flow. They cause the flow velocity to be increased in the vicinity of the pipe walls.
This effect is utilized when flushing systems as increasing the flow rate causes particles that have been deposited on the wall to be loosened and swept away.

4.2 Dispersion Effect

The oil used for flushing has to have a dispersion effect so that particles are dislodged and transported off. Special thin-bodied mineral-oil-type flushing oils can contribute instrumentally to improving the flushing effect. They lower the adhesion force between the dirt particles and the pipe wall. By virtue of their excellent surface wetting properties, they creep into between the dirt particles and the wall, thus causing the particles to become dislodged. Experiments have shown that by changing the flushing fluid from an operating fluid to a flushing oil, component/system cleanliness can be increased by a factor of 4. Flushing oils of this type have to then be closely matched to the hydraulic medium used as failure to properly match the two may lead to the following:

marked foaming

filter blockage

clogging of the system

4.3
Flushing of All Ducts and Surfaces

When setting up the inspection and testing plan, it has to be ensured that all surfaces and ducts are wetted during flushing.

4.4
Pulsating Flow during Flushing

Pulsating flow or the reversal of the flow direction also results in improved removal of adhesive particles. In so doing, the main effect is achieved by virtue of alternating forces being applied to the particles to be dislodged. The same effect can be achieved via ultrasonic equipment or other vibration-generating equipment.

Fig. 20

The flushing of pipework/hoses and hydraulic systems can be done using a HYDAC Flushing Unit.

The following is performed:

Pressure testing

Flushing

Documentation of the flushing results

4.5
Performing a Cleanliness Check on a Flushing Stand

The cleanliness of components and systems which undergo function testing can be determined on a flushing or function test stand (= flushing stand).

This method is used for pumps, cylinders, transmissions, control units, power steering units, valve blocks, etc.

Once it is ensured that the flushing stand possesses the properties indicated above, an analysis is conducted as described below.

Prior to the analysis the flushing stand is cleaned to a defined high cleanliness level so that the basic contamination of the test system does not affect the measurement results. Then this basic cleanliness is computed and recorded.

4.5.1
Determining Overall
System Contamination

The sampling site for an automatic particle counter is defined as a site upstream or downstream of the test item, which is subjected to a direct flow. The following is performed if the analysis result is to be additionally subjected to gravimetric analysis:

the entire test fluid is collected and filtered through an analysis membrane

or an inline membrane retainer featuring the analysis membrane is integrated in the return-flow line.

Now the test item is tested in accordance with the inspection and testing plan, during which the cleanliness classes are recorded.

Example 1:

The schematic below shows the analysis performed on a pump test stand.
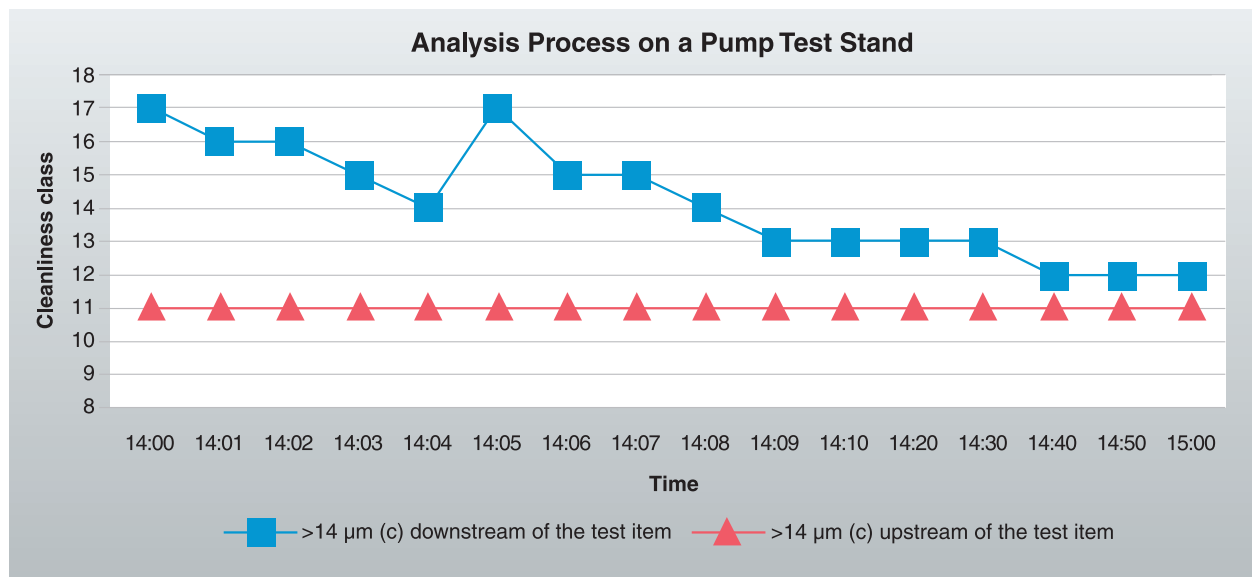
After 5 minutes of testing the pump speed is increased to the maximum speed. This causes particulate contamination to be dislodged. The system becomes increasingly cleaner. Particulate contamination is still being released after 1 hour of testing (standard test time: 10-15 min.), consequently the cleanliness of the return-line fluid (blue = downstream of the test item) never achieves the same cleanliness as upstream of the test item.

This method is suitable for checking the cleanliness of items being delivered quickly and simply in series testing, documenting it and then concluding the flushing procedure when the target value is achieved. By integrating the measurement circuit in the manufacturing instrumentation and control system it is also possible to quickly detect any deviations and initiate suitable measures. The goal of continuous cleanliness monitoring is to monitor process reliability with regard to system cleanliness upon delivery.

A specification like this also enables increased system contamination to be responded to quickly. If these measurements are only conducted once a day, a whole day's output might be affected and have to be remedied. The result is unnecessary costs that can be avoided by integrating a continuous measurement procedure.

When conducting a reference measurement, the system is disassembled after the test run, if possible, and the individual components analyzed using the flushing method.

Fig.21

Analysis Process on a Pump Test Stand

Cleanliness class (y-axis: 8 to 18)

Time (x-axis): 14:00, 14:01, 14:02, 14:03, 14:04, 14:05, 14:06, 14:07, 14:08, 14:09, 14:10, 14:20, 14:30, 14:40, 14:50, 15:00

— >14 µm (c) downstream of the test item   — >14 µm (c) upstream of the test item

Example:

As-supplied condition: 17 / 15 / 12 according to ISO 4406:1999

1. Warning point: 18 / 16 / 13 for 3 successive measurements

2. Stop signal: When exceeding 18 / 16 / 13 limit cleanliness class in 2 successive measurements.

5 Contamination Monitoring

The reliability of hydraulic systems can be impacted heavily by particulate contamination during the running-in phase. The risk of outages during the first minutes or hours of operation is particularly high as the foreign particles introduced or created during the assembly process are still relatively large and can thus cause sudden outages. During continued operation, these large particles are ground into smaller ones, the result being that damage can be caused to the surfaces of system components during this crushing process. The consequences are leakage, degraded output and efficiency, or a shortening of the component's service life.

In many cases, microfiltering is used to quickly clean the system fluid during commissioning. However, in the automotive sector this is not possible in systems integrated in cars (exceptions: transmissions and motors).

This is where contamination monitoring is key in the manufacture and assembly of these systems. By implementing contamination management a major portion of particulate contamination introduced during manufacture and assembly can be removed. The result is cost savings by virtue of smaller performance deviations on test stands caused by the sudden clogging of particles in sensitive system components plus lower costs associated with warranty and non-warranty courtesy work. For more information, refer to section 9.

Below follows a description of the goal, design and performance of a process audit.

Contamination monitoring extends to checking the cleanliness status of all manufacturing and assembly processes considered relevant in this connection. (cf. analysis methods, described in section 4) Proper preparation and informing all those involved are key in contamination monitoring.

5.1
Planning and Design

First, the objective of contamination monitoring is specified, e.g.

Determining the current situation

Checking fluctuations between batches

Checking washing processes

Comparing the target with the actual situation
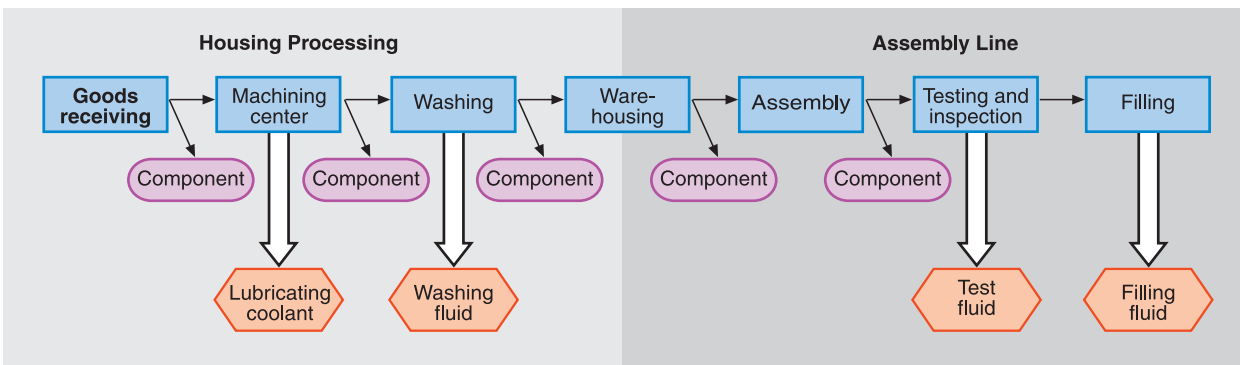
Determining the sampling point

During the planning and design phase, the sampling points for components and taking liquid samples are determined using a production plan or operation sheet. The employees to be involved in contamination monitoring are informed of the objectives and procedures.

NOTE:
Manufacturing has to continue in the same manner, meaning that no additional cleanliness levels, etc. are to be integrated. The purpose of contamination monitoring is not to check the quality produced by the employees but rather determining the causes and sources of contamination.

The following schematic is an excerpt of a manufacturing line:

5.2
How Sampling is Done

A representative sampling is taken of the fluids and components; the samples are stored so as to prevent any further contamination. Special sampling bottles are used for the fluid samples; the components are stored in defined clean packaging.

The analysis is performed in accordance with the methods specified in sections 3 and 4 and the findings recorded.

5.3
Inspection of the Manufacturing and Assembly Line

Properly trained or experienced individuals while inspecting the manufacturing and assembly line can detect some sources of contamination. That is why such an inspection is conducted during the audit. The findings made during inspection are then compared with the results in hand.

Fig. 22

The schematic above shows the manufacturing processes and the corresponding sampling points. However, in actuality sampling is more comprehensive, i.e. the description includes the number of the Minimess fittings at which sampling is done, for example.

5.4
Results

The contamination monitoring results describe the condition at the time at when sampling is done. The findings might look like this:

Fig. 23

Housing Processing

Goods receiving → Washing → Storage

Component → 10 mg / 760 µm

Component → 7 mg / 200 µm

Component → 7 mg / 200 µm

Washing fluid → ISO 18/15/13 / 100 µm
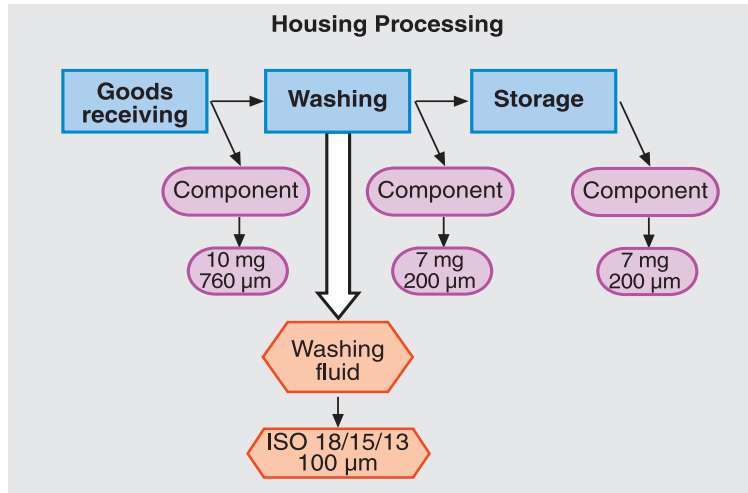
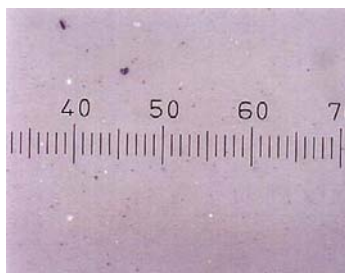This chart shows an excerpt of the housing manufacturing process. The component samples are taken upstream and downstream of the washing station. The findings show that the washing station performs well and that it is well positioned here. Subsequent storage is not being done properly as the portion of particulate contamination is almost double.
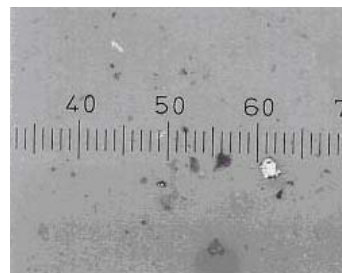
Fig. 24

Micro-photograph
Analysis membrane

Particulate contamination of a component **prior to** storage

Fig. 25

Micro-photograph
Analysis membrane

Particulate contamination of a component **after** being in storage for 2 weeks

6 Drafting a Cleanliness Specification

By applying a cleanliness specification to components and the system it can be ensured that as-supplied quality is constant.

The following should be borne in mind when drafting a cleanliness specification:

State of the art

Benchmarking — what do others do?

Inclusion of previous experience — if available —

Defining and implementing contamination management as an "official project"

Inclusion of all hierarchy levels

Accurate documentation of how the specification was developed

Developing clear-cut definitions

Next, it has to be determined which components in the system are the most sensitive. Frequently it is not possible to achieve the same level of cleanliness throughout the system during assembly.

If suitable filtration takes place **upstream** of the sensitive components, an area of low-contamination-sensitive components can be defined upstream of this filtration and an area of highly contamination-sensitive components downstream of the filter.

These individual components or system areas should be subdivided into sensitivity areas.

Category	Designation	Description
A	low particle-sensitivity	For the most part low-pressure systems with large gap tolerances
B	particle-sensitive	Low-pressure systems with small gap tolerances
C	high particle sensitivity	High-pressure systems with small gap tolerances and with exacting demands made of safety and security systems

A maximum particulate contamination value is specified for each of these cleanliness categories.

A car motor illustrates this subdivision below:

Category	Motor area
A	Air Coolant water circuit
B	Low-pressure oil circuit
C	Diesel direct injection High-pressure oil circuit

In addition, the fluid cleanliness ratings of the individual system and process fluids are defined.

6.1 Establishing Cleanliness Specifications

The following parameters are defined in the cleanliness specifications for the components:

1. Goal of the cleanliness specification
2. Applicability (system designation)
3. Extent of inspection and testing; inspection and testing cycles
4. Sampling
5. Analysis method
6. Evaluation method
7. Accuracy
8. Analysis fluids to be used
9. Documentation
10. Limit values

This specification has to be made for each individual system; consequently a few things are discussed which have to be borne in mind.

Work instructions concerning sampling, analysis and evaluation methods should be described in detail so as to ensure that sampling is always done in a uniform manner. In addition, the analysis results depend on the analysis fluid and method, particularly when it comes to component analysis. Documentation should be done using forms so that all the results are readily accessible. Example of a form for entering findings:

Contamination Management

System	**Power steering**	Analysis date	**31.01.2001**

Component analysis

Component	**Rack**	Sampling point	**After washing 1**
Part no.	**Xx12345**	Sample taken by	**Joe Smith**
Batch size	**1**	Sampling date	**30.01.2001**
Analysis method	**Ultrasonic**	Lot designation	**01-2001**
Analysis fluid	**COLD-02**	Analysis fluid vol.	**1,500 ml**
Negative value	**0.2 mg**	Membrane filter rating	**7 μm**

Evaluation method

Inline particle counting	Automated particle counting of the analysis fluid	Automated particle counting of the membrane	Manual particle counting
			X
Gravimetry	X		

Result			
Gravimetry	8	mg/component	
Largest abrasive particle	350	μm	

	No. of particles/component		
	> 50 μm	> 100 μm	> 200 μm
Actual value	**100**	**10**	**3**
Limit			**0**

System fluid

System	**Washing 1**	
Sampling point	**Flushing bath**	
Sample taken by	**Joe Smith**	
Sampling date	**30.01.2001**	

Measurement method

Inline particle counting	Automated particle counting of the analysis fluid	Automated particle counting of the membrane	Manual particle counting
			X

Result:

ISO 4406	**22/20/18**	NAS 1638
Largest abrasive particle	**300 μm**	

Signature: Date:

Example of a Cleanliness Specification

1. Goal of the cleanliness specification
The goal in implementing this cleanliness specification is to achieve a constant level of cleanliness for system X.

2. Applicability
(system designation)
This specification applies to system X including its series A, B, and C. It extends to all components whether sourced or manufactured in house. It also specifies the system fluids of system X with regard to their cleanliness.

3. Extent of inspection and testing; inspection and testing cycles
5 samples/month of each component are to be taken and analyzed. If the supplier parts achieve a constant cleanliness value after 6 months, the sampling cycle can be extended to sampling every 2 or 3 months. An analysis of the entire (assembled) system is to be done at least once a week prior to delivery. Checking of the fluid cleanliness should optimally be done on a continuous basis.

4. Sampling
Sampling of components is to be done at goods receiving. Sampling of components is to be representative; samples are to be packed in a dust-tight manner and sent in to the laboratory. The fluid samples are to be taken at the sampling points indicated in the inspection and testing plan, or an instrument to be connected directly.

5. Analysis method
The flushing method is to be used for component analysis. The surfaces of the component are flushed in a defined clean environment using x ml of the test fluid (XY) — which possesses a cleanliness of xx — under a pressure of z bars as specified by the inspection and testing plan. The flushed-off particulate contamination is collected on an analysis membrane and subjected to gravimetric analysis.

Representative samples are taken of the system fluids at the specified sampling points. All testing parameters are specified, i.e. the duration of testing, what is tested, the pressures, speeds. When conducting static inspection and testing, e.g. pressure testing in pipeline and hoses, make sure that a flushing effect is present so that the cleanliness of these components can be determined, i.e. the static pressure test has to be followed by a dynamic flushing process in order to analyze the actual quantity of particles which is flushed out of the component.

6. Evaluation method
In the component analyses the analysis membrane is dried until it achieves a constant weight, and then cooled in a defined dry environment and weighed. This procedure is repeated subsequent to filtration. The weight differential indicates the "gravimetric contamination" of the component. This is followed by visually examining the analysis membranes through a microscope and measuring the longest particles.

Evaluation of the fluid samples is done in accordance with ISO 4405, ISO 4407, ISO 4406:1999 or NAS 1638.

7. Accuracy
The analysis equipment has to be brought to a residual dirt content of 0.2 mg prior to conducting the analysis so that the measurements taken of the component samples are sufficiently accurate. This is determined by performing a negative control, i.e. flushing the equipment without testing. When the result of the analysis drops below 0.5 mg, the batch size is to be increased and thus a mean value of the results computed.

8. Analysis fluids to be used
The following analysis fluid should be used for the component analyses: ABC-XX, with a cleanliness class of 14 / 12 / 9 and no particles > 40 µm.

9. Documentation

The documentation of the results is to done using a result sheet (cf. sample).

10. Limit values

The components are subdivided into 3 cleanliness classes:

Category	Designation	Description
A	low particle-sensitivity	For the most part low-pressure systems with large gap tolerances
B	particle-sensitive	Low-pressure systems with small gap tolerances
C	high particle sensitivity	High-pressure systems with small gap tolerances and exacting demands

The following cleanliness specifications apply to each of these classes (fictitious example).

Category	Gravimetry	Particle sizes
A	20 mg / component	Max. 4 particles > 500 µm Max. size: 400 µm No fiber bundles
B	10 mg / component	Max. 4 particles > 400 µm Max. size: 800 µm Fibers up to 4 mm
C	5 mg / component	Max. 4 particles > 200 µm Max. size: 1,000 µm Fibers up to 2 mm

The transmission components are subdivided into the individual categories below:

Group A: crankcase sump

Group B: intermediate housing, transmission housing, coupling flange

Group C: valve plate, valve housing, centering plate

Fluid samples:

At the end of the test run, the transmission fluid may not fall short a cleanliness rating of 17 / 15 / 13 (c) according to ISO 4406:1999. The system is to be operated using a cleanliness rating of 18 / 16 / 14 (c) according to ISO 4406:1999.

11. Procedure to be followed in the event that the specification is not adhered to

The supplier components are to be returned to the supplier in the event that the specification is not adhered to. If this procedure results in production delays, the components will be cleaned and analyzed by us at the supplier's expense.

HYDAC

7 Sources of Contamination in the Manufacturing and Assembly of Hydraulic Systems

Particulate contamination can enter a power fluid system in various ways. The main sources of ingression are shown in the following diagram:

Fig. 26

Sources of Contamination in the Manufacturing of Hydraulic Systems
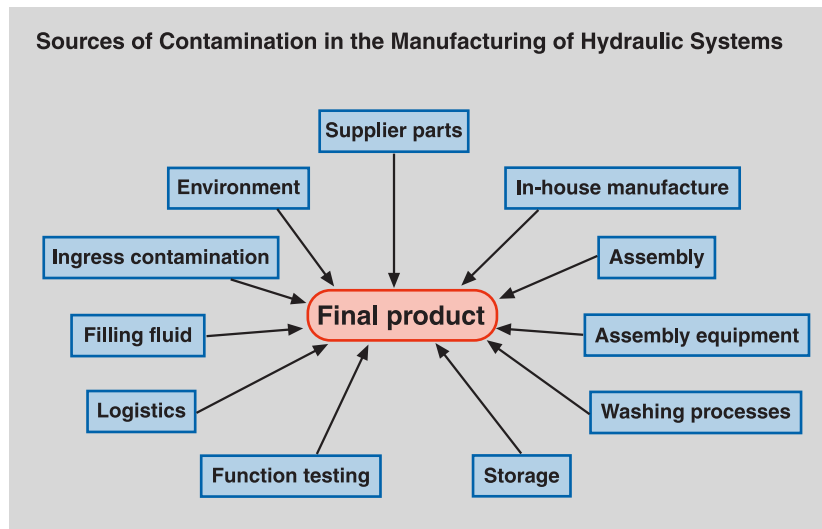
Some of these sources of contamination can be eliminated in a simple, cost-effective manner.

The following applies in **Contamination Management**:

What isn't allowed to enter the system doesn't have to be removed.

7.1 Preventing the Ingression of Contamination in the Manufacturing and Assembly of Hydraulic Systems

The ingression of contamination in the manufacturing and assembly of hydraulic systems can be eliminated in a cost-effective manner in various process steps.

Storage and Logistics

When storing and transporting the components and systems care has to be exercised to make sure that they are properly sealed shut or well packed. Transportation and storage packing has to be in keeping with the cleanliness status of the individual components.

Assembly of Systems and Subassemblies

The assembly of these systems is to be done in accordance with system requirements. This means that the assembly and mechanical fabrication areas have to be separated if necessary in order to prevent the ingress of contamination. The assembly stations have to be kept clean to a defined cleanliness and those working in these areas have to

wear special, lint-free clothing. The assembly equipment has to be properly cleaned so as to prevent the ingress of dirt here, too.

Raising the Awareness of Employees

In order to achieve the objective of "defined cleanliness of components and systems" it is important that employees at all levels be involved in this process. Frequently, a considerable savings potential is contained in the employees' wealth of ideas and experience — particularly those working at assembly lines and in fabrication. Experience has shown that when employees are able to identify with the objective being striven for, they are more able to help in implementing it quickly and effectively.

Environment — Air Cleanliness

In some cases it will be necessary to set up a clean room for the final assembly of very contamination-sensitive systems, e.g. fuel systems, brakes shock absorbers, etc. This has to be decided on a case-by-case basis. However, in many cases performing the measures described here suffices.

7.2
Removal of Particulate Contamination from Hydraulic Systems (Practical Experience) and Components

Generally speaking, particulate contamination is removed from a hydraulic system via filtration. Various types of filters are used depending on the amount and type of contamination.

Belt filter systems or bag filters are used when large quantities of contaminants are involved (e.g. washing machines, machine tools). These filters have the job of removing the major portion of contaminants (often in kg) from the system. These filter types are also used for prefiltration purposes.

In most cases, these coarse filters do their job of "removing a lot of dirt from the system" very well. However, microfiltering also has to be done if a constant defined high level of cleanliness of the system fluid is to be ensured.

Whereas microfiltration ensures quality, the job of coarse filtration is to control the quantity of contamination.

7.2.1
Cleaning System

Individual components are freed of clinging contamination in cleaning systems (particles, remainder of machining or corrosion protection fluids, etc.). Cleaning can be done by employing various mechanical methods (e.g. spraying, flooding, ultrasonic methods) using various cleaning fluids (aqueous solutions or organic solvents). The temperature and duration of cleaning also have a decisive effect on the cleaning effect. These factors have to be carefully matched and optimally tuned in order for a favorable cleaning effect to be achieved in an economical amount of time.

Fig. 27
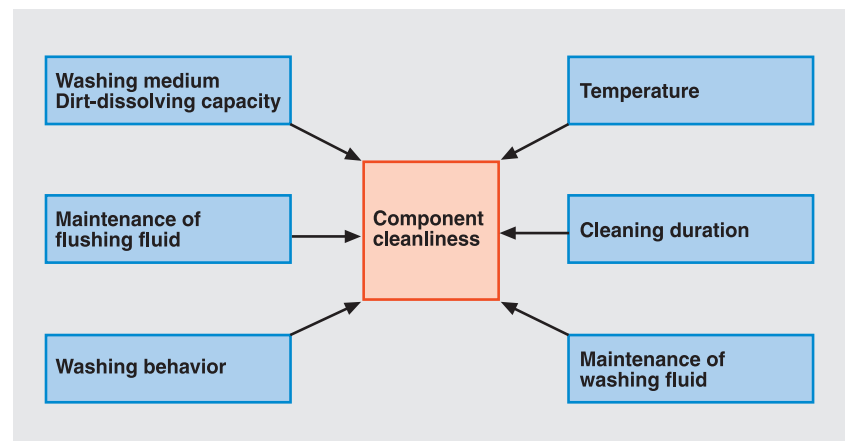
Various studies of washing processes have shown that some of these for the most part cost-intensive processes aren't worthy of the name. Some people refer to washing processes as "particle distribution processes". This "property" was detected in examinations of components sampled upstream and downstream of a washing process.
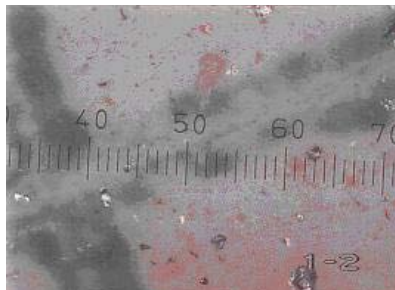
Example: Pipeline flushing
after bending

Fig. 28
Micro-photograph
Analysis membrane
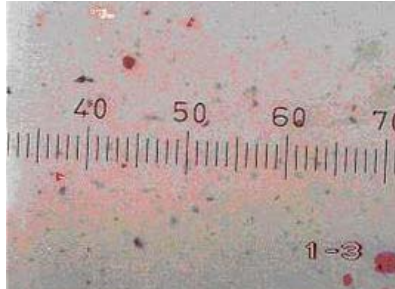
Pipe has been sawed and washed

Fig. 29
Micro-photograph
Analysis membrane

After sawing and washing, the pipe
is bent and flushed.

There are two possible responses
in a case like this:

1. Discontinue the washing process
when component cleanliness
becomes worse after washing than
before.

Advantage:
temporary cost savings

The best alternative:

2. Optimize the process
The following should particularly be
borne in mind when optimizing
washing processes:

cleanliness of the washing, flushing
and corrosion protection fluid

mechanical aspects
(e.g. clogged washing nozzles)

suitability of the washing process
for the components undergoing
washing

filtration of the washing and
flushing fluid

When purchasing washing
systems, make sure to specify the
component cleanliness to be
achieved and the maximum
contamination load of the washing
fluid in terms of mg/l or a
cleanliness class.

Washing systems used to be
subdivided into micro and micronic
washing. This was a very imprecise
definition of the cleaning
performance to be achieved.
Nowadays the permissible residual
dirt quantity of the cleaned
components is defined.

Specifying these residual dirt
quantities is done as follows:
mg/component, mg/kg component,
mg/surface units or particle
concentrations in various size
ranges. In addition, the maximum
sizes of the particles are defined
which can be on the washed
component, e.g. max. 3 particles
> 200 µm, no particles > 400 µm.

These values cannot be achieved
unless the factors indicated above
are matched and fine-tuned. The
following factors additionally have
to be borne in mind: environmental
protection and labor safety, local
situation relating to space and
power available, and the target
throughout rate.

The cleanliness of the washing and
flushing fluids also has a decisive
impact on the cleaning
performance of the washing
machine.

However, we are concerned here
only with the maintenance of the
washing and flushing fluids.

The following methods are used in standard maintenance:

Cleaning method	Solid contamination	Liquid, non-dissolved contamination (emulsion)	Liquid, dissolved contamination (emulsion)
Filtration			
Belt-type filter	X		
Bag/backflush filter	X		
Micronic filter (tube/disk filters)	X		
Ultrafiltration	X	X	
Distillation	X	X (for high boiling point differences)	X
Separator	X	X (density difference)	
Oil separator		X	
Coalescer		X	

The type and composition of the cleaning medium is to be taken into account in selecting the fluid maintenance options indicated above. When using ultrafiltration, it has to be borne in mind that separating out the cleaning substances cannot be avoided in certain cases. In addition, ultrafiltration can only be used for precleaned washing media since the performance of the separating membranes is degraded when they are loaded with particulate contamination.

Using Filtration as Fluid Maintenance for Separating out Particulate Contamination

Bag and backflush filters in various microfilter ratings are the standard equipment used in the maintenance of the fluid of washing systems. Although these filters are suitable for removing large quantities of contamination from a system, they are not suitable in most cases for maintaining defined cleanliness classes. Owing to their design, they do not offer much resistance; i.e. the counterpressure built up across the filter is very low, below 1 bar for the most part. That is why this filter type is frequently used in the main (full) flow when feeding cleaning fluid into the washing or flushing chamber. The filter housings are equipped with pressure gauges for monitoring the proper functioning of the filter.

Bag filters pose the risk that overloading can cause the bag to be destroyed and large contaminant quantities released.

That is why it is advisable to additionally define minimum change intervals and to regularly monitor the cleanliness of the washing fluid in addition to the standard parameters like pH value or microbial count.

Residual dirt values of cleaned components are increasingly being defined and specified as an acceptance criterion for the cleaning system. It is of paramount importance that constant adherence be maintained to these values. It is also imperative that the quality of the cleaning fluid be maintained at a constant, high level.

This can be achieved by the targeted use of microfilters featuring a constant, absolute separation rate. For the most part, tube filters or disk filters are used. The advantage offered by these filter types as compared to standard hydraulic filter elements is their high contaminant retention rate owing to their depth effect.

Thanks to the high contaminant separation rate offered by these filter types, they remove a high amount of contamination from the washing fluid; this causing the filters to become quickly exhausted and blocked.
A sufficiently long service life coupled with high washing fluid cleanliness can be achieved by combining filters for removing the main portion of contaminants from the system with absolute microfilters.

A typical example is described below.

At a leading automotive supplier, the camshafts were to be cleaned to a defined cleanliness of 9 mg/component. Point of departure:

Technical specifications of the washing machine present on site:

Tank volume:	80 l
Pump delivery rate:	250 l/min (centrifugal pump)
Washing agent:	Ardox 6478 – chemetall
Concentration:	2.3 – 3 %
Bath temperature:	ca. 50 °C
Filtration:	Backflush filter downstream of pump, 50 µm filter rating

Process data:

Bath change frequency:	1 time/week
Throughput:	3,000 – 4,000 components/day
Wash cycle:	15 s/component

Challenge:

Clogging of the tank

Quality no longer sufficient after 2-3 days

Fluctuation in the contamination content of the components upstream of the line: 30 – 50 mg

Cleaning costs per component not to be any higher than € 0.008

Cleaning costs could not be allowed to increase, although quality still had to be improved

Goal of optimizing the cleaning line:

Achieve a residual contaminant value of a maximum of 9 mg/camshaft
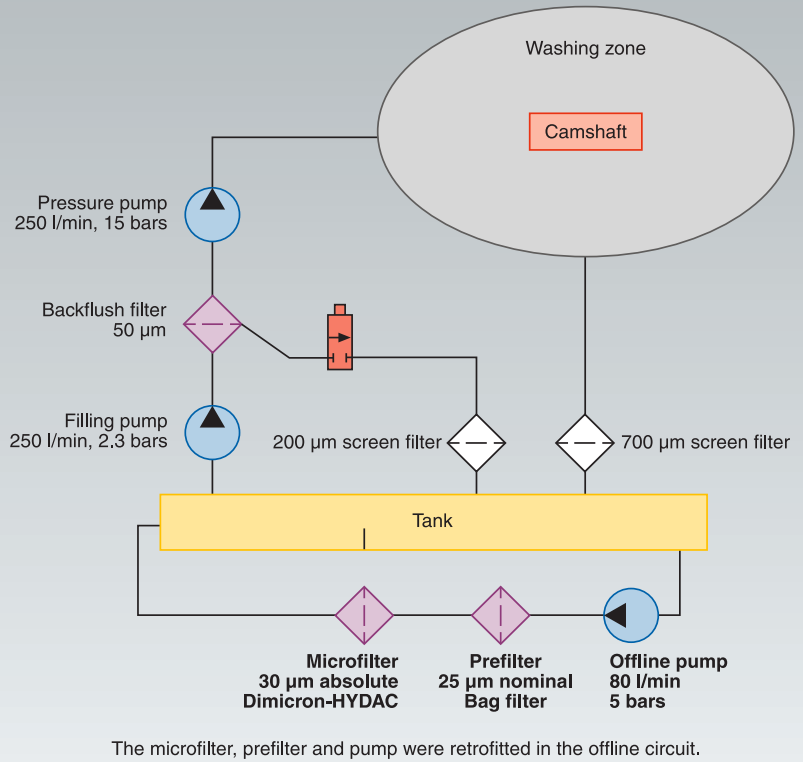
Cleanliness of washing fluid of < 30 mg/liter

Extend the service life of washing fluid, i.e. save costs associated with changing the fluid

Prevent clogging of the tank, e.g. save cleaning time

For process reliability reasons, a low-maintenance cleaning system was to result which enabled the camshafts to be cleaned to a residual contaminant content of 9 mg/component, this to be done cost-effectively.

Optimization of a Camshaft Cleaning Line in Order to Achieve Defined Residual Dirt Content Specifications

Washing zone

Camshaft

Pressure pump
250 l/min, 15 bars

Backflush filter
50 µm

Filling pump
250 l/min, 2.3 bars

200 µm screen filter

700 µm screen filter

Tank

**Microfilter
30 µm absolute
Dimicron-HYDAC**

**Prefilter
25 µm nominal
Bag filter**

**Offline pump
80 l/min
5 bars**

The microfilter, prefilter and pump were retrofitted in the offline circuit.

Result of Optimization

The service life of the cleaning fluid was extended from 1 week to 8 weeks. There was no more clogging of the tank. Changing the bath fluid was done on account of the increased chloride content, not on account of contamination.

The residual contaminant values of max. 9 mg/camshaft and max. 30 mg/liter of bath fluid (when using a 5-µm membrane for analysis) were achieved and maintained at this level.

The service life of the economical bag filters is 2 weeks. The service life of the HYDAC Dimicron® absolute filter is 8 weeks.

Economic Efficiency Analysis

	Investment €	Recurring costs €	Savings/year €
Off-line filtration	5,000.00		
Filtration costs		7,500.00	
Extension of the service life of the bath			10,000.00
Lower reworking costs			These costs can't be quoted.
Down time of the washing machine for cleaning			These costs can't be quoted.

By optimizing the fluid maintenance of this washing line, an improvement in quality was achieved at no added cost and without comprising process reliability; i.e. the washing costs remained at € 0.008/camshaft, as was specified at the beginning of the project.

This example shows that prior to any such optimization or in new facilities the cleanliness of the components upstream of the system, throughput, technical details, targets have to be known and defined, for only in this way can the success of such an endeavor be ensured.

7.2.2
Function Testing

Most systems come into contact with the hydraulic fluid during initial system filling or function testing. This process affords the manufacturer a substantial opportunity to decisively impact the final cleanliness of the entire system. By employing suitable filtration of the filling and test fluids, system cleanliness can be quickly optimized upon delivery or commissioning.

The cleanliness of the final product can be controlled via function testing in the same way as by a washing machine.

Some companies have the following motto:

"The test stand is our last washing machine."

This statement might be true, however it is an expensive approach in practice. Yet when performing process reliability measures for supplying systems with a defined cleanliness, this is the first approach.

The following schematic illustrates the basic setup of most test stands.

On a function test stand not only function testing is performed but the components and systems are run in as well. A frequent side effect of this is the flushing effect of the system undergoing testing. By employing targeted fluid maintenance and cleanliness monitoring, this flushing effect can be used to ensure that systems possess a defined, constant cleanliness status upon delivery.

Cleanliness monitoring provides information on the process stability of the upstream fabrication and cleaning steps. Frequently, continuous monitoring of test fluid cleanliness results in the cleanliness of the entire system as supplied being documented. This approach is used in mobile hydraulics, turbines or paper machinery upon delivery or during commissioning in order to demonstrate to the final customer that his system is being supplied with the specified cleanliness.

Fig. 31
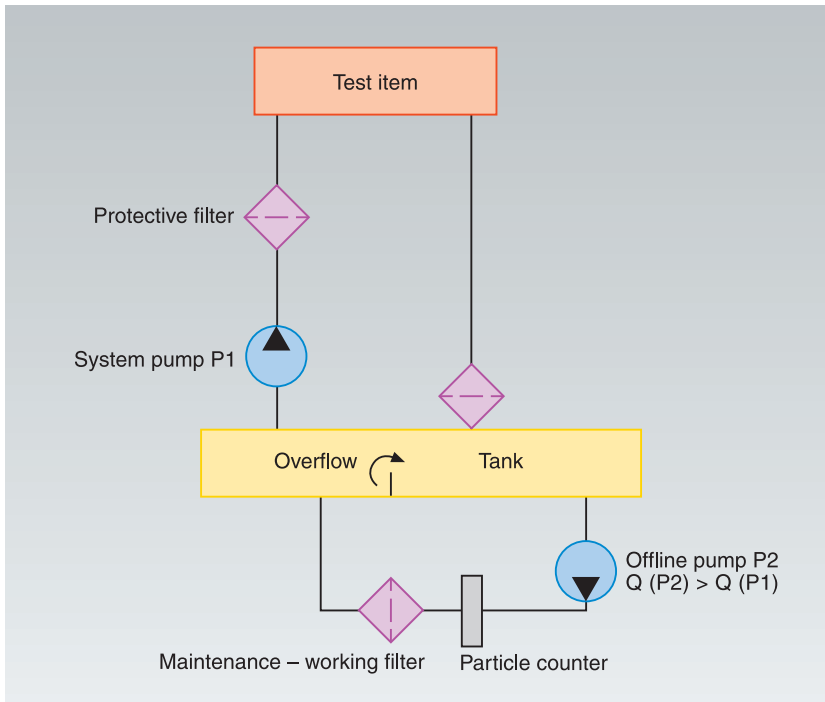
1. Example:

The following study illustrates the cleaning process of a pump during commissioning*:

The cleanliness of the test fluid upstream of the test item is maintained at a cleanliness rating of 16 / 14 / 11 (c). After 5 minutes of testing the pump speed is briefly increased to the maximum speed. The test run is concluded after 10 minutes.

In this case, the dirt content of the test item amounted to 1 mg/kg component weight upon the conclusion of the test run.

* Section 4, Analysis of the Cleanliness of Systems on the Flushing/Test Stand.

Fig. 32
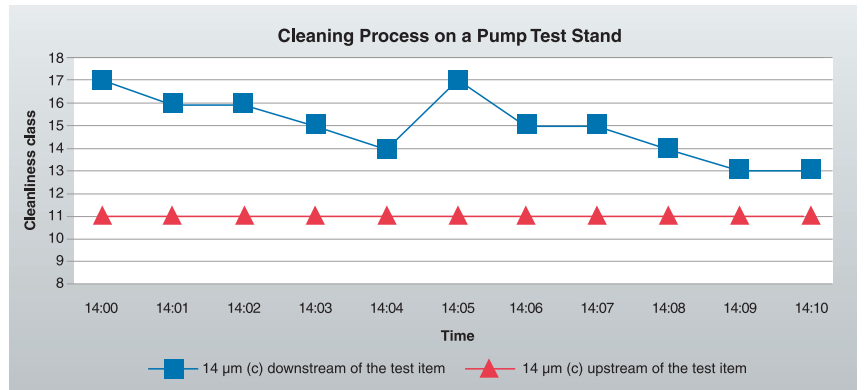
As the schematic above shows, the particle concentration continuously drops during the first 4 minutes of the test run. The particle concentration jumps when the pumps are turned up to full speed after 5 minutes. The next 5 minutes are again used for cleaning the system.

Cf. also section 4.5 Performing a Cleanliness Check on a Flushing Stand. The flushing/test stand described there served as a test object for determining the optimal flushing time in the function testing of pumps.

Fig. 33
Example: Valve test stand with 5-µm filtration

Fig. 34
Cleanliness class achieved by the test fluid: NAS 3

Now the following can be asked: "How clean are the valves that leave this test stand?"

The flushing procedure can be monitored by occasionally disassembling the valves in a defined clean environment and evaluating the dirt content of the individual components.

7.3
Storage, Logistics and Ambient Conditions

Unfortunately, improper component storage is not uncommon. Seals and gaskets which arrive at the assembly line clean and packed in bags are unpacked and filled into containers which are dirty for the most part as this involves less work and effort.
In most cases, these factors are not taken into consideration and substantial savings potential that could be easily utilized through improved packaging and storage is overlooked.

7.4
Supplier Parts and Components Manufactured In-house

Suitable cleanliness specifications for internally produced and sourced parts enable the ingress of contamination into systems to be minimized right from the beginning.

8 Commissioning Flushing

This method is most frequently chosen for large systems in order to minimize wear during commissioning.

The filtration of the flushing stand has to be designed so that during subsequent analysis the contaminants flushed out of the system undergoing testing are removed and other measurements aren't skewed. As an alternative, cleanliness can be measured and recorded upstream and downstream of the test item during the entire measurement sequence.

In the example below, the specified sampling point was located directly downstream of the pump and an online particle counter connected.

Examination of the Hydraulic System of a Mobile Crane

Fig. 35
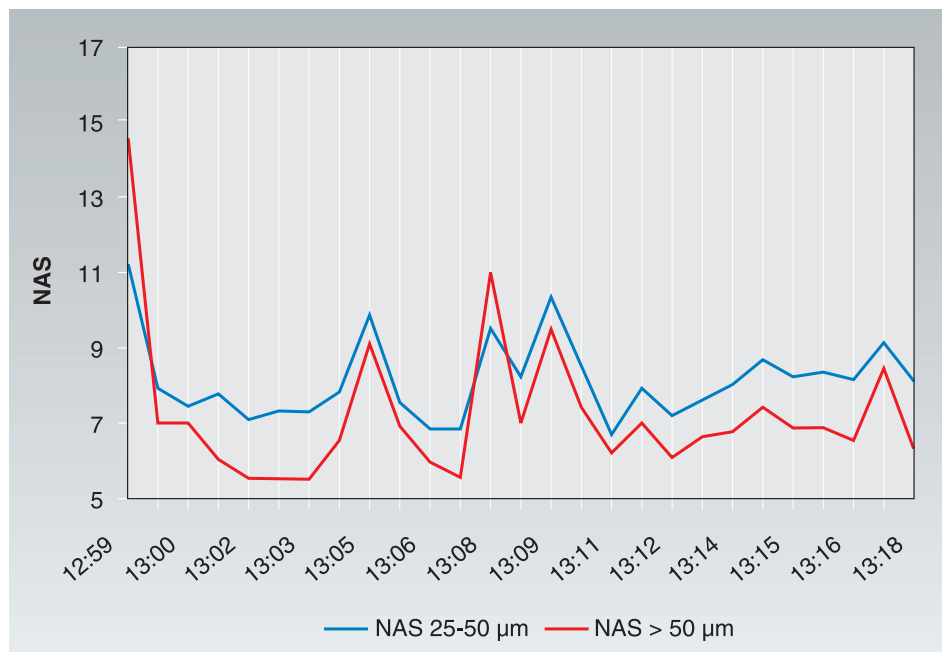
The crane jib was extended after 6, 8 and 10 minutes. The graph clearly shows that every time a new area was brought on line contaminant sediments were flushed out.

When a system's characteristic curve/behavior is known, cleanliness testing can be performed at the end of function testing and, thus, system cleanliness described subsequent to commissioning. This method enables process control to be implemented quickly and reliably during series testing/commissioning. The cleaning curve plotted over time is an indication of the ingress of contaminants during assembly.

9 Economic Efficiency Analysis

The core aspects of contamination management are a cost analysis and efficiency review. The following costs are considered in the cost analysis:

- Warranty and non-warranty courtesy work
- Energy costs (e.g. cooling and reheating of washing machines during fluid changes)
- Test stand costs (test item time)
- Costs of the tools and dies of machine tools (increased wear due to high particle concentrations)
- Fluid costs (washing machines, test stations, machine tools)
- Labor costs (reworking, cleaning of washing machines, machine tools, etc.)
- Filter costs

The following economic efficiency analysis describes the success of contamination management as illustrated by a manufacturing line in the automotive industry with an output of 3,000 systems/day. Manufacturing is done 260 days/year. A contamination review showed that the cleanliness of the function test stand fluid, the intermediate storage conditions and a machining process had to be optimized. The optimization costs are shown below:

The next step involved forwarding the cleanliness specifications to the suppliers, who received orientation training and are periodically monitored.

The results of optimization:

- Less tool wear in surface machining
- Longer service life of the machining fluid
- Enhanced effectiveness of the downstream washing processes as less dirt had to be removed thanks to optimized storage and machining
- Longer intervals between changing the washing and flushing fluids, consequently "Saturday shifts" could be dispensed with
- Fewer outages at the test stand, i.e. the system is checked up to 3 times when performance deviations occur. These "idle cycles" were reduced by 90 %, thus resulting in increased productivity.
- Drop in warranty and non-warranty courtesy work by 50 % as the main reason for the outages turned out to be particulate contamination, which resulted in leakage and imprecise control in the system.
- Shortening of the test stand time.

Unfortunately we were not permitted to publish the detailed data behind these savings. Following from an economic efficiency analysis conducted by the customer in-house, savings of € 0.60 per system were achieved.

When expressed in terms of the company's annual output of 780,000 systems, this translates into savings of:

€ 468,000

This economic efficiency analysis also includes the expenses associated with contamination management (seminars, consulting fees, analysis costs).

	One-off investment [€]	Recurring costs / year [€]
Function test stands (5)	6,500 * 5 = 32,500	7,500 * 5 = 35,000
Storage conditions Coverings for the pallets Washing machine for cleaning the pallets	2,500 50,000	25,000
Machining process Manpower/cleaning Filtration	750 * 7 = 5,250 1,250 * 7 = 8,750	2,000 * 7 = 14,000
Consulting expenses	10,000	1,750
Total:	109,000	75,750

Contamination Management in Practice

In the sections above we discussed the impacts of particulate contamination on the service life and reliability of hydraulic systems, how the cleanliness of fluids on components can be specified, and how contamination monitoring is performed.

Deploying contamination management results in the following tasks for all participants in the production process:

Suppliers:

Ensuring the defined as-supplied condition of products.

Selecting the packaging of products to be supplied so that no additional contamination occurs during transportation and storage.

System vendors and manufacturers:

Careful transportation, handling, storage and unpacking of products.

Keep products clean after they are unpacked or after seals/plugs have been removed.

Assemble/install the components in a suitably clean environment.

The following example shows how these individual parts can be combined in contamination management.

Description of the Point of Departure:

System X has been successfully manufactured and marketed for years. During the past few years, System X has been developed further and a new generation, System Y, created. Y features improved performance properties, is more compact than X, and operates at higher system pressures than X. The result is that System Y is somewhat more sensitive to particulate contamination.

This is reflected in increased performance deviations during function testing. This deviation no longer occurs when Y is passed through the test stand a second or third time.

An investigation of the matter has shown that this unwanted behavior is the result of coarse particulate contamination.

The goal of contamination management is now to improve the degree of cleanliness so that this undesirable behavior no longer occurs on the test stand and the associated costs of warranty and non-warranty courtesy work are reduced.

Step 1: Analysis of the Test Fluid

The cleanliness of the test fluid is determined. The analyses show that the test fluid cleanliness upstream of the test item amounts to a cleanliness rating of 22 / 20 / 18 according to ISO 4406, the largest metallic particles are 400 µm in size, and the largest fibers measure 3,000 µm.

Step 2: Optimizing the Function Test Stand

By additionally integrating bypass microfiltration, which maintains test fluid cleanliness at 15 / 13 / 10, 95 % of the performance deviations can be prevented.

This also results in a drop in warranty and non-warranty courtesy work.

Step 3: Lowering the Filter Costs at the Test Stands

By performing a contamination monitoring audit, it might be determined a large amount of particulate contamination is being transported into the system by the manufacturing processes and sourced components. This particulate contamination has to be removed from the system at the function test stand, which functions here as the last washing operation. This results in costs that could otherwise be avoided.

A concept is developed in which the washing and machining processes and intermediate storage are optimized.
A cleanliness specification along with a test plan for system fluids is drafted. This specification is forwarded to external as well as internal suppliers and the components supplied with a defined, constant cleanliness.

Step 4: Integrating Particle Counting in Quality Assurance

A particle sensor is integrated in the function test stand for the purpose of continuous quality control of the as-supplied quality of System Y. A limit is defined for the maximum contamination of the test fluid in the return line. Intervention can be done immediately if this value is exceeded, thus ensuring that no contaminated systems leave the factory.

Random sampling is done to check the supplier quality and non-conformant components returned to suppliers or washed in-house at the supplier's expense.

Step 5: Economic Efficiency Analysis

Contamination management started off with analyzing the costs associated with warranty and non-warranty courtesy work as the result of increased malfunction at the test stands.

These costs are reanalyzed after optimization and compared.

The savings achieved through optimization are briefly described in Economic Efficiency Analysis.

The cost savings in that case amounted to ca. € 468,000/year. This optimization process lasted ca. 2 years.

Step 6: Documentation and New Projects

The contamination management findings are collected in a database and used in the development of new systems.

The defined maximum residual dirt content becomes standard in new systems in the same way that dimensions, surface grades and tolerances have been. This residual dirt content is primarily in reference to the specification that applies to System Y.

The specification is adapted in keeping with the experience gained with the prototypes. Cleanliness and cleaning costs are primarily determined by the design of new systems.

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