Contamination Control - A Hydraulic OEM Perspective

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This paper reviews the potential effects of contamination on high performance hydraulic systems. Design considerations at the component and system level are discussed based on practical examples.

1. Introduction

Modern hydraulic control systems are making increasing use of servo and proportional control valves. These devices are inherently at the critical stage of controlling the manufacturing process and quality of the end product. Proportional valves are also found in ancillary functions for materials handling where time is of the essence. Failure of control valves will cause very expensive loss of production many times more than the cost of prevention.

The principal means of prevention is the maintenance of the hydraulic fluid with regard to cleanliness and chemical composition. Cleanliness is a function of selection of the appropriate filters for the valve and application environment. Chemical properties relate to factors such as water content and various forms of break down that can occur due to chemical contamination, excessive heat or working of the fluid.

These factors can be monitored effectively at a relative low cost by laboratory tests offered by filter companies and suppliers of hydraulic fluids.

Design of the filtration requires a careful understanding of the effects on valves, valve design, circuit layout and operating environment. If these factors are carefully considered it is possible to achieve high reliability and long life in some of the most difficult environments.

It is important that there be a close evaluation of components and circuit layout to achieve the optimum solution. The key system elements are:

> [1] Servo valves and proportional valves are usually the most important area for filtration design. Inherently they perform critical control functions for the machine; requiring consistent operation and high reliability.
>
> [2] Pumps and motors can vary from rugged fixed displacement gear or vane pumps to sophisticated variable displacement piston equipment with fine clearances [Table 1] and high capital cost. In many instances the pump may be the crucial factor for planning filtration.
>
> [3] Ancillary valves and components that comprise the balance of the hydraulic circuit are generally satisfied if groups [1] and [2] above are suitably protected. There may be some considerations with regard to type of component for example in safety circuits where the choice of a seated [poppet] valve is mandatory to avoid lock up due to silting.

From practical experience, the focus has been on the design issues for servo valves and proportional valves with secondary consideration for pumps, motors and other devices. Clearly there are cases where the pumps or motors will be of major importance; however although outside the scope of this paper, the principles as applied to valves can be similarly applied to any hydraulic components.

Item	Typical Clearance	
	microns	in.
Gear Pump(Pressure Loaded) Gear to Side Plate Gear Tip to Case	 1/2-5 1/2-5	 0.00002-0.0002 0.00002-0.0002
Vane Pump Tip of Vane* Sides of Vane	 1/2-1 5-13	 0.00002-0.00004 0.0002 -0.0005
Piston Pump Piston to Bore** Valve Plate to Cylinder	 5-40 1/2-5	 0.0002 -0.0015 0.00002-0.0002
Servovalve Orifice Flapper/Nozzle Spacing Spool to Sleeve**	 130-450 40-80 1-4	 0.005 -0.018 0.0016 -0.003 0.00004-0.00015
Control Valve Orifice Spool to Sleeve** Disc type* Poppet Type	 130-10,000 1-23 1/2-1 13-40	 0.005 -0.40 0.00004-0.0009 0.00002-0.00004 0.0005 -0.0015
Actuators Hydrostatic Bearings Antifriction Bearings* Slide Bearings*	50-250 10-25 1/2- 1/2-	0.002 -0.010 0.00004-0.001 0.00002- 0.00002-

* Estimate for thin lubricant film
* * Radial clearance

Table 1: Typical critical clearances for hydraulic components

2. Effects of Contamination

The results of contamination can be simply divided into two problems which in turn become the goals of our design:

2.1 Short term failures

These are the random and often unpredictable failures due to jamming of a spool or plugging of an orifice. This is the most costly form of failure since it will lead to an unplanned shut down of manufacture and can cause machine damage as a result of uncontrolled actuator movements.

Typical mechanisms are:

2.1.1 Particle jamming - where contamination becomes lodged in the fine clearances between the spool and body [or bushing]; particles may also block control orifices to cause a 'hard over' condition or loss of control pressure. It is important to understand the size of clearances and driving forces to overcome particles, when deciding on the filtration to solve this type of problem. It is not so easy to quantify the magnitude of forces on spools for example but there is some empirical data available that can help to estimate the order of magnitude of forces that need to be overcome [Figure 1].

Particles that can cause this failure often cause more than the functional failure. Since they can become wedged in the spool, it is common that permanent damage is done to the control lands of the valve that also means an expensive repair or a new valve is needed.

This is usually resolved with a non - by pass high pressure filter with a Beta rating selected to remove particles of the size that can block the function of the valve.

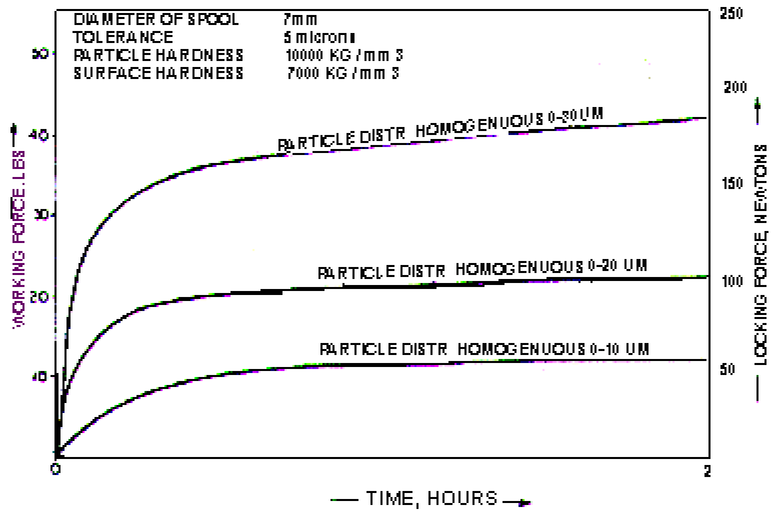


Figure 1: Spool locking forces due to particle jamming.

2.1.2 Silting - this phenomenon occurs with any spool type valve. If we hold a spool in a fixed position with high pressure across the lands, there is a gradual build up of fine 'silt' particles that can lock the spool within 5-10 minutes. This is the reason why poppet type solenoid valves are used in safety circuits where long stand times can be involved. A conventional solenoid (or the return spring) will not move the spool after 3-5 minutes[Figure 2].

Silting is proportional to pressure differential, poor filtration, rest time and valve design.

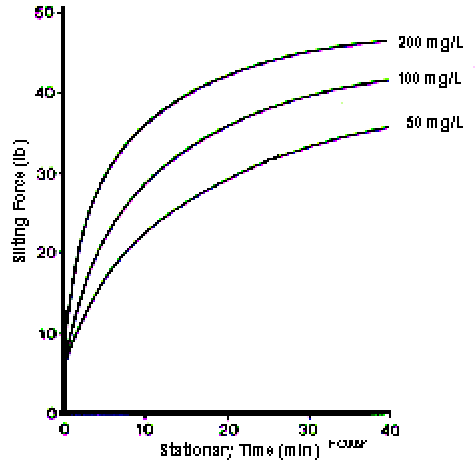


Figure 2: Spool locking forces due to silting

2.2 Long Term Failures

All valves will ultimately wear in any system no matter how good the filtration. Our goal is to maximise that period to ensure that we achieve long life of the valves and reliable product quality.

It is not easy to provide a simple statement of valve life as this depends on: filtration, operating environment, valve design [eg: spool travel], control system performance requirements, operating fluid, frequency of operation and operating pressure.

We can quote some examples of what can happen with identical valves.

Example [a] plastics blow moulding machine using a long stroke servo valve for control of ‘parison’ thickness - we have many cases where good filter maintenance has been applied such that the time between overhaul has been up to 10 years. The same application where the system has not been correctly maintained can suffer from catastrophic failures within months or weeks [usually particle jamming due to heavy contamination].

Example [b] in the steel industry there are documented cases of fluid incompatibility [chemical erosion] causing failures in weeks; poor flushing of pipework modifications leading to failure in hours or days. In this latter case the system was cleaned and filtration upgraded such that we are now seeing a life of years in a very severe operating environment.

So what are the longer term effects?

Apart from stopping the valve from working there can be a gradual build up of other ‘varnish’ or silt type contaminant that degrades the control qualities of the valve such as threshold and hysteresis. This will directly impact on system accuracy and repeatability.

The second problem is the erosion of valve parts that lead to loss of control system performance. Typical wear areas are:

a) Feedback ball connection in mechanical feedback servovalves. A flat spot will develop on the feedback ball causing loss of fine control and actuator oscillation.

b) Control lands will wear to increase null leakage and some loss of pressure gain performance.

Wear is a combination of high flow velocity and contamination. This can be minimised by removal of the fine silt level particles, either through return line filtration or an off-line filter system.

Finally it is common to provide a 'last chance' filter to protect the internal parts of a valve in the event of catastrophic system failure. These filters are typically made of wire mesh and built into the body of the valve in the pilot stage supply line [Figure 3]. Although they are quite coarse [servo valve 35-70 microns, proportional valves 200 microns] there will be a gradual accumulation of contamination over an extended period of valve operation. This may result in a loss of valve response and can also cause a valve offset which in turn will affect positioning accuracy of the controlled actuator. As a general rule the main system filters should be protecting the 'last chance' filter. There have been instances where this filter has needed frequent service and blamed for being too small! This is clearly the symptom and the real cause is inadequate contamination control in the overall system.

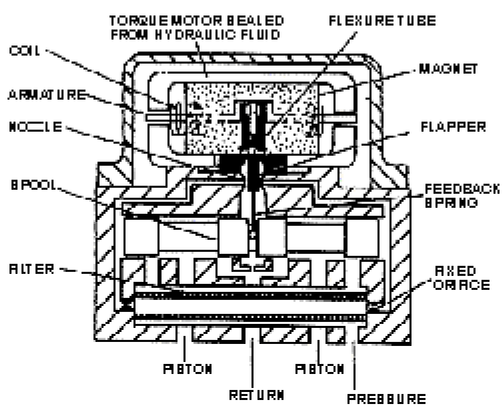


Figure 3: Mechanical feedback servovalve

2.3 Summary of Contamination Effects

Short Term

- particle jamming
- silting

no warning, catastrophic for equipment, production and personnel

Protection against short term failures is provided by a non-pass pressure line filter as well as appropriate consideration of the valve design.

Long Term

- wear
- silt
- last chance filter

effects control system performance with regard to - null offset

- pressure gain curve [valve]
- null leakage [valve]
- slower response
- oscillation or instability

Long term effects cannot be eliminated , however by proper design it is possible to maximise the useful life of the valve before service or repair is required. This requires the effective application of silt level filtration.

3. Valve Design

Selection of the best valve design for an application has an important influence on control system performance as well as defining the filtration requirements and likely contamination sensitivity. A good understanding of how and why the valve works will provide maximum benefits to the overall design solution being developed for the customer. On the contrary, over simplification or generalisations about relative contamination tolerance of one group of valves versus another will inevitably lead to costly problems.

For an example, when selecting pumps for high performance hydraulic systems we should make a careful analysis of design [piston, vane, gear], operating pressures, operating fluid, duty cycle, bearing life and operating environment to name a few of the parameters. We know that there is the potential for premature failure if the pump selection does not take account of detailed issues. In a high pressure, heavy duty cycle application there are major differences in pump life depending on piston configuration and bearing design.

In the same way, there are significant variations in the system accuracy and reliability when we compare different manufacturers of servovalves and proportional valves. We must balance design goals with component details, component costs and overall system costs. Some of the important features are included in this section and serve as an example for analysing new designs, not covered here.

Again we should look for both short term and long term effects on the valve. It is assumed that the valve has already been evaluated to meet the control system performance with regard to static and dynamic characteristics. These parameters are also a direct function of how the valve has been designed and manufactured.

The starting point is the specifications provided in the manufacturer's data sheets together with a good quality cross sectional drawing or photograph to assist in understanding how the valve works. There are three principal areas to consider:

[1] Internal forces

[2] Spool position control

[3] Design tolerances

There are some other factors that relate to contamination sensitivity which tend to share common performance across the major manufacturers; often due to the basic laws of physics! Common actuation devices like proportional solenoids tend to generate the same forces for a given valve size due to similar dimensions and materials being used. There is also very little variation in the hardness of materials such that two valves with similar tolerances and performance, will have comparable wear behaviour. Notable differences have been the development of ceramic parts for valves operating on high water content fluids. However, such features are not available for conventional electro-hydraulic valves.

3.1 Internal Forces

Understanding the forces within the valve that provide for correct operation and those that resist operation, is most valuable for understanding optimal filtration requirements. Forces determine both short term and long term performance for [a] contamination sensitivity and [b] threshold/resolution.

A check list of forces that influence filtration design includes:

3.1.1 Spool Driving Forces that may be derived from electromechanical devices [solenoid, force motor, voice coil, torque motor] or by hydraulic piloting.

For example: a review of a CETOP 5 [NG10] proportional valve spool from a number of different manufacturers reveals a wide range of possible force levels.

Spool Driving Device	Spool Driving Device
proportional solenoid [force controlled]	5..10
proportional solenoid [position controlled]	10
linear force motor [position controlled]	40
hydraulic pilot [reduced 5..20 bar]	5...20
hydraulic pilot [full supply 210 bar]	200

Table 2: Spool driving force comparison

The risk of failure needs to be equated to potential resisting forces due to particle jamming [Figure 1], silting [Figure 2] and flow forces [Bernoulli]. Contamination related failures can be reduced by a superimposed dither to the valve command as well as good silt level filtration. Some specialised, single stage valves used in steel mills employ specially contoured bushings to cancel out Bernoulli forces that would otherwise limit the size of the control spool relative to the actuating voice coil. This is however very expensive to manufacture and the majority of valves on the market use two or three stage designs to provide stable control against such flow induced forces. Limited flow compensation is achieved by controlling flow through metering notches machined in the spool lands or by profiling the spool and its control lands.

An indication of how the flow forces can affect control is shown in Figure 4 where the step input to a CETOP 5 proportional solenoid valve has induced severe oscillation even at the catalogue specification.

This means that apart from the control problems, the proportional solenoid has little or no margin to overcome additional contamination induced forces

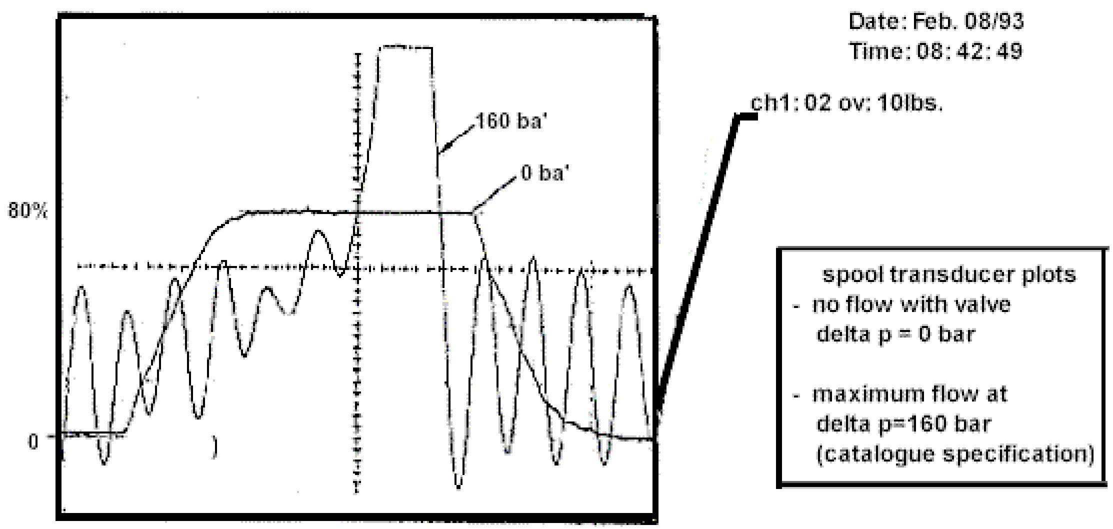


Figure 4: Step response of CETOP5 proportional solenoid value

3.2 Spool Position Control

For both servovalves and proportional valves the spool is capable of being positioned anywhere over its total designed stroke. How the spool is moved and held in that position will have a direct influence on the cost of manufacture, system accuracy and contamination sensitivity. Three methods are used and described in the following.

3.2.1 Open Loop [OL] or 'non-feedback' [Reference 6.3]

Typically the spool is positioned by a force balance between a proportional solenoid and an opposing spring. Some two stage valves apply the driving force by proportional hydraulic pressure controlled by a miniature pressure reducing valve which has a proportional solenoid for setting its values.

Open loop [OL] is:

- lowest cost to manufacture
- has the worst total valve error [Table 3]
- is more contamination sensitive [no margin over the force to move against the spring]
- common for low cost proportional valves but rare in servo valves

Errors are due to variations and changes with the positioning spring with temperature and changing valve pressures. Additional forces to overcome spool friction effects must be created before the valve moves to a new position resulting in high threshold and hysteresis values.

Maximum spool driving forces are only available when the valve is commanded to maximum opening. For low signal, fine positioning the forces are proportionally lower thus making the valve more sensitive to contamination than valves with closed loop [MFB, EFB] control. This type of valve is suited to low cost, frequent 'soft switching' type applications.

Design	Most Common Use	Spool Control		Null Stability			Valve Un-certainty	Pressure Gain	Total Valve Error
		Hysteresis	Threshold	D T 55 C	D Ps 70 bar	D Pt 35 bar			
Servovalves									
EFB		0.5	0.1	2	1		2	3	5
MFB		3	0.5	2	2	2	2	3	5
OL		6		11	4*	4*	15	3	18
Proportional Valves									
EFB		1	0.3	1.5			2	5	7
MFB		3	2				2	5	7
OL		6		11	4	4	15	5	20

* D Ps= 40%Ps, D Pt= 10%Pt

Table 3: Valve design comparisons with percentage errors

3.2.2 Mechanical Feedback [MFB]

By providing closed loop control of the spool position via a mechanical feedback spring [Figure 3 & 5] the valve characteristics and contamination sensitivity can be improved significantly. The majority of servovalves in operation in industrial and aerospace applications still use this technique with high reliability in a variety of environments.

Hydraulic pressure derived from the pilot stage [flapper -nozzle, Servo Jet , deflector jet] ensures that high spool driving forces are generated for mechanical closed loop positioning. The increased complexity makes the design more expensive to manufacture than open loop [OL] but lower cost than electrical feedback [EFB].

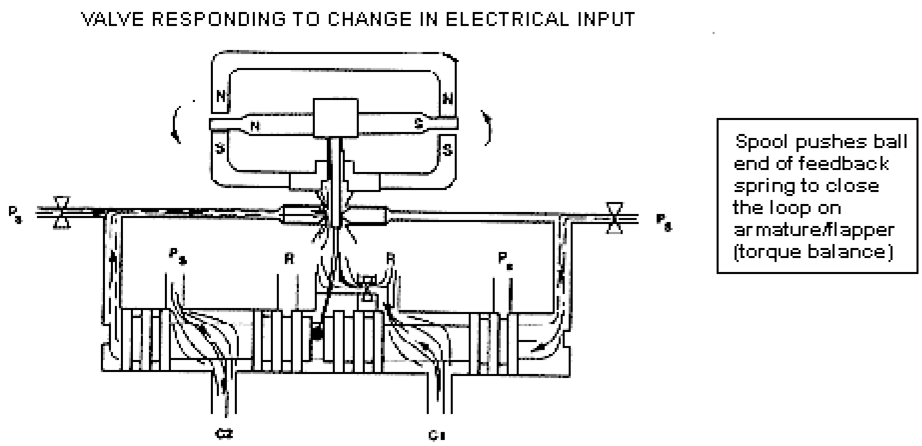
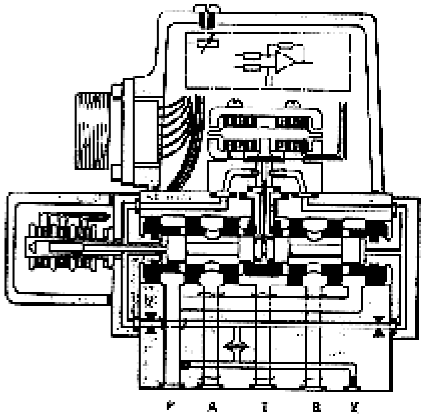


Figure 5: Principle of operation for MFB serovalve

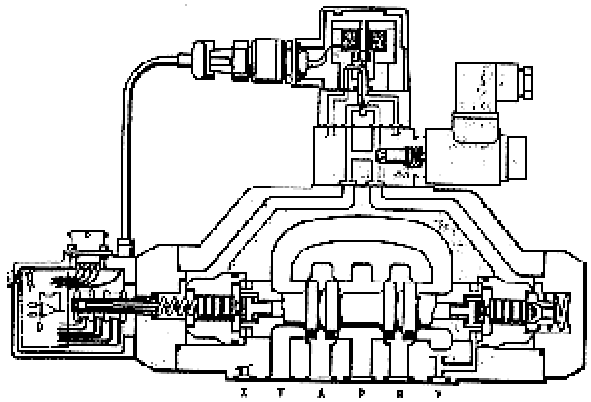
3.2.3 Electrical Feedback [EFB]

Various spool actuating devices can be used with electrical closed loop positioning to achieve the best control and contamination resistance. Spool position is measured by a short stroke transducer [LVDT] and closed loop electronics provide control either external to the valve or increasingly on-board [Figure 6]. EFB valves are becoming the preferred solution for both servovalves and proportional valves in many industries.

It is interesting to compare the same approach to spool control [OL, MFB or EFB] across a range of manufacturers catalogues. The comparisons shown in Table 3 were compiled from data sheets for many different designs and manufacturers. For a given solution there is a close correlation of specifications.



Servovalve



Proportional Valve

Figure 6: Electrical feedback valves

3.3 Design Tolerances

Finer tolerances will be more susceptible to wear and the potential for particle jamming. These dimensions are a function of original design and manufacturing objectives such as :

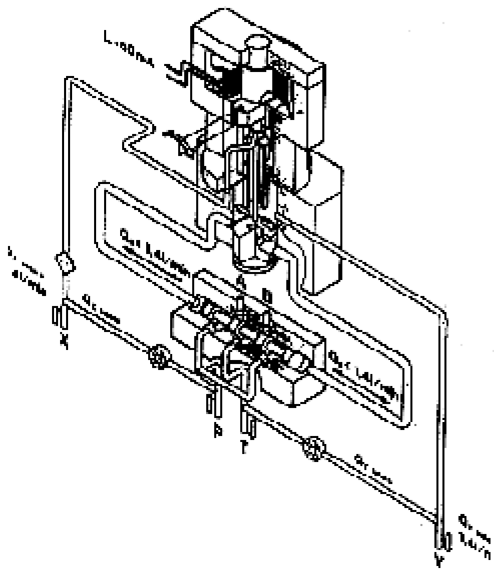
[1] nozzle diameters and exit clearances [Figure 7]

[2] spool diametral clearance [Table 1]

[3] spool travel - from 0.250 for high performance servovalves to 5-10mm for proportional valves. Shorter stroke means faster response, but finer manufacturing tolerances.

[4] spool control land overlap - which ranges from 10-20% overlap proportional valves to 'axis cut' [zero overlap] servo valves which require special protection of the lands to maintain performance. Zero overlap valves are used in the pilot section of some proportional valves so that protection requirements can be similar for parts of servovalves and proportional valves.

All of the tolerances are related to both short and long term functionality. They will be an important factor for evaluation of either servovalves or proportional valves with regard to filtration design.



- filter 200 microns
- inlet tube 3.2 mm dia
- jet nozzle 450 microns dia
- jet to receiver clearance 350 microns
- receivers 650 microns dia

Figure 7: Typical clearances for Servo Jet pilot valve

3.4 Summary for Valve Design - [designer's check list]

Internal forces that may influence filtration design:

- solenoid /force motor / voice coil directly to a spool
- torque motor to jet or nozzle device
- Bernoulli flow forces
- hydraulic pilot pressure - what percentage of supply pressure is applied ? what is the actuating area ?
- likely contamination force levels

Typical areas to consider:

- nozzle diameters and exit clearances [nozzle to flapper; jet to receiver]
- spool diametral clearance
- spool travel
- control land overlap
- poppet versus spool valve

4. Contamination Control

The purpose of hydraulic filtration is to improve system reliability by removing "damage causing" particles from the fluid.

No system is free of contamination and sources of contaminate fall into four major areas-

- built into the components and subsystems
- generated during assembly of the system
- generated by maintenance
- ingression, eg. cylinders are dirt pumps, via reservoir breather.

Oil in a typical hydraulic system can best be described as ‘a concentrated abrasive slurry using oil as a carrier." Traditional filters have done little to control the concentration of abrasive wear-causing particles. As 95% of the particles in most systems are below 10 microns, it is necessary to utilise filtration which can effectively control "silt" particles.

Particles in the silt range have been proven to be the primary cause of equipment downtime caused by abrasive wear, valve sticking and oil degradation. The prevention of silt circulation and build up can increase component life 10 to 100 fold.

4.1 Designing the Filtration System

There are five fundamental steps to be taken when designing the filtration for a particular hydraulic system.

4.1.1 Identify sources of contamination and apply filters to provide additional protection if needed.

- pressurise the reservoir or use a breather bladder for systems operating in contaminated environments.

- break away couplings are sometimes used for quick change of gauge control actuators in rolling mills. Pressure filters should be included in the hydraulic lines to such actuators to protect the servovalve.

4.1.2 Review the requirements of the servovalve or proportional valve according to Section 3 of this paper. Control valves should be broken down into their individual stages to determine the filtration requirements of all critical components.

The common features of a **servovalve** or zero overlap valve are:

- precise control edges requiring high accuracy fitting and nulling of the bushing spool assemble (zero overlap/axis cut)
- static performance(low hysteresis, threshold, resolution)
- high dynamics (implies short spool travel

For **proportional valves** it is usually found that filtration of the pilot stage satisfies most applications. However valves using reduced pressure for the main spool positioning and direct drive proportional solenoid valves often require good main stage filtration due to low driving forces.

- precise control edges may be used as part of the pilot valve but not in the main stage
- static performance of the pilot valve needs to be protected.
- a short stroke spool may be used in the pilot but main stage tolerances are relatively large.

4.1.3 Overall system layout including flow and duty cycle. Sometimes the servosystem is part of a much larger system and consumes a relatively small volume of oil. Under such circumstances it may be more practical to build a separate hydraulic system. Intermittent high flow systems should use an off- line filter system rather than trying to use the main return line flow.

4.1.4 Define the cleanliness goals required for the equipment and operational objectives (Fluid Contamination Level ISO4406).

4.1.5 Select filters to achieve the cleanliness levels and in accordance with the circuit design (Refer to Section 4.2).

4.1.6 Establish maintenance and monitoring procedures to achieve fluid contamination levels (ISO4406).

4.2 Filter Selection

The ideal arrangement is summarised as follows:

- Use a 15 micron (Beta 15^{3} 75) high pressure filter just before the valve or critical parts of the valve (e.g. pilot).
- Use a 3 micron (Beta 3^{3} 75)low pressure filter on return or bypass line.

This is justified on the basis that:

1. the valve can accept the odd particle up to 25 microns. The Beta 15^{3} 75 high pressure element (without bypass check valve) ensures this even when contamination causes the pressure drop across the filter to exceed the 7 bar indicator level.
2. it is neither practical nor economical to try to clean the oil with the small, relatively expensive, high pressure element. The cheaper, low pressure element is many times larger and has the potential to filter continually and under more ideal condition. (Steady flow and lower velocities increase filtration efficiency).

- In the case where large changes of oil volume in the reservoir can draw in airborne contaminant, it is suggested that a 3 micron low pressure element be used as an air breather.
- Using high flow 3 stage valves may make full flow filtration prohibitively expensive. In this case use an external supply to the pilot valve and fully filter this flow; the third stage being much less contamination sensitive.
- Always use dirt alarms/pressure switches to enable rational changing of elements.
- Use cheaper low pressure elements to flush the system on start-up. Remember that new oil is perhaps filtered to 40 microns and is thus "dirty oil".
- The tank volume should be **flushed** around through the filter at least 100 times, changing the element when indicated by the pressure switch (dirt alarm).

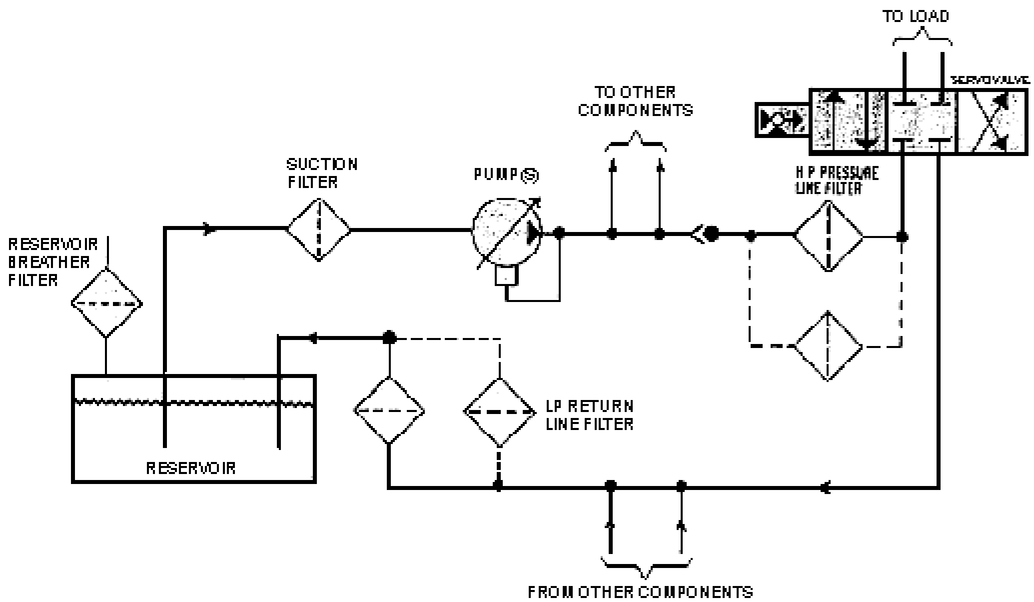


Figure 8: Recommended hydraulic system filtration

Short term protection of critical components	15 micron pressure filter, non-bypass, with high pressure differential element, clogging indicator installed in the pressure line immediately upstream of the valve.
Long term wear protection	3 micron low pressure filter, by-pass to protect the element, clogging indicator, installed in the return line or offline with a separate recirculating pump

4.3 Servo valves

Most industrial servovalves tend to specify a range of cleanliness levels from "normal operation" to "longer life". However the "longer life" specification is preferred from a design objective and the higher level of contamination ("normal operation") tends to give an indication of short term objectives.

Recommended cleanliness levels are not uniform for servovalves due to the design variances discussed in Section 3 but, the Table 3 provides a comparison of levels (ISO4406) that can be expected:

	Maximum Contamination Level		
servovalves	Valve A	Valve B	Valve C
"normal operation"	16/13	15/12	14/11
"longer life"	14/11	15/12	13/10
Automotive Industry- servovalves	13/10		
Proportional Valves			
"normal operation"	19/15		
"longer life"	16/13		
General Hydraulics	18/15		
Dirty Oil	21/18		

Table 3: Comparison of contamination levels to ISO4406

4.4 Proportional Valves

Proportional valves have a broad variety of needs that should be reviewed stage by stage.

- Main stage (hydraulically piloted) can tolerate the same level of cleanliness as the general system hydraulics - usually determined by life and reliability of the pump.
- Pilot stage (or single stage valves) have varying needs depending on actuation principles

  - servo jet/flapper nozzle should be ISO4406 19/15 to 16/13.

  - spool control (fine metering edges) should be 16/13 to 14/11.

Tables 4 and 5 are summaries of catalogue reviews for leading suppliers of proportional valves. It is interesting to note that regardless of valve design that there is 100% agreement between the five brands with respect to the ideal filtration and cleanliness specification.

Conclusions based on the worst case quoted need some caution and must be qualified by evaluation of design details discussed in Section 3. In the final analysis most manufacturers fall within a similar top band.

Manufacturer	Valve series	NAS class	ISO class
Bosch	proportional valves zero overlap valves	10-8 9-7	19/15 to 17/14 18/15 to 16/13
Moog	servo-jet		19/15 to 16/13
Parker	D*F		19/15 to 16/13
Rexroth	4WRA, 4WRD, 4WRE, 4WRZ	9-7*	18/15 to 16/13*
Vickers	proportional valves		16/13 or cleaner

Table 4: Proportional valves - recommended cleanliness class

In Table 4, "Bosch" quote 16/13 for zero overlap valves which should be equivalent to the requirement for their proportional valve pilots. However for some reason they quote a slightly higher class (17/14) as a rule for their proportional valves. This higher class conflicts with companies like Rexroth, Parker and Vickers who are offering valves of identical design in terms of clearances, spool driving forces and materials.

Manufacturer	Valve Series	Recommended Beta Rating (> 75)*
Bosch	proportional valves zero overlap valves (as used for pilots)	10-25 microns 10 microns
Moog	servo-jet pilot	10-25 microns*
Parker	D*F	10-25 microns
Rexroth	4WRA, 4WRD, 4WRE, 4WRZ	10 microns
Vickers	proportional valves	only quote cleanliness class

* where a range is quoted the lower value is for "longer life"

Table 5: Recommended filters for proportional valves

Note for Table 5:

(a) Filter specification depends on desired cleanliness class and how that is to be achieved relative to filter type, circuit location (pressure line, return line, circulation), filter dirt retention and Beta rating.(b) Pilot stage or pilot valve should use a high pressure filter (without bypass, but with dirt alarm) mounted in the main flow and if possible directly upstream of the valve.

5. Conclusions

Effective filtration for high performance hydraulic systems means :

- understanding the valve design
- setting and maintaining cleanliness objectives
- appropriate filtration for the environment
- no short cuts with filter quality or replacement elements
- regular monitoring and service

Good filtration will **always** give the lowest machine running cost and greatest reliability for the end user of hydraulic systems.

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