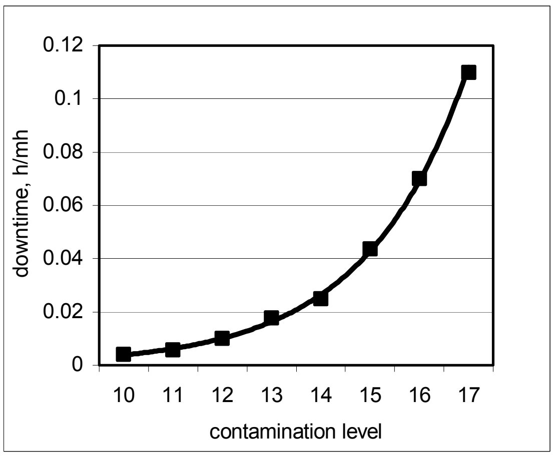
Fluid and Air Purification in Industrial Hydraulic Drives

Grigori Brodski
AGA Engineering Inc., Chestnut Hill, MA, USA

The experience of exploitation of industrial systems shows a strong relation between reliability of hydraulic power drives and the working fluid contamination level. Possessing the large database for the exploitation of 48 mining and construction machines during 5 years [1,2], we are able to make some quantitative conclusions on the topic (Fig. 1.)



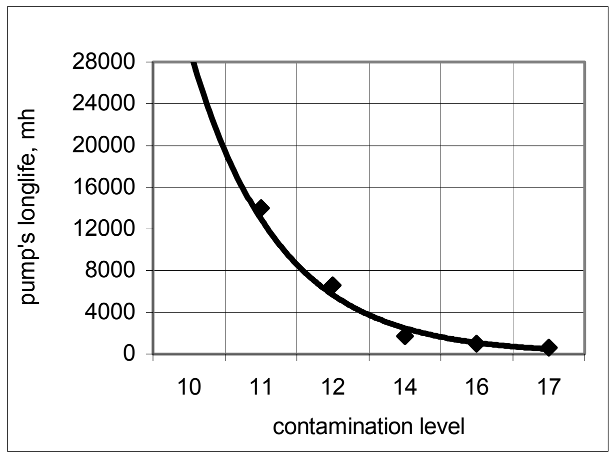


Fig.1. Reliability parameters for hydraulic drive depending upon the fluid contamination level

Not only is the mechanism of the direct influence of contaminants on the reliability of hydraulic systems complex, deviating; it also has various feedbacks. From the analysis of said mechanism it is possible to conclude that the major parameters of fluid contamination which are to be monitored:

- Total quantity of the particles (contamination level)
- Particle distribution according to their size (gravimetric curve)
- Physical composition of the contamination (metal, abrasive, cloth etc).

The producers of the mobile machines distress their attention on the purification factor, and, as a consequence, on the development of special filtration systems for hydraulic drives. The main stages here are:

- Definition of the reasonable technical demands for the fluid purification
- Appropriate design of the filtration system
- Development of maintains order and special equipment for the exploitation of the filtration system.

Technical Demands for Fluid Purification in Hydraulic Drives

Nowadays, the base for the formation of the initial requirements for the filtration system is the information about clearances in tribological triads of hydraulic components. The usual position here is when the absolute filtration rating is less than the smallest clearance [3]. In other words, the manufacturers specify the contamination level and filtration rating corresponding to the nominal reliability of hydraulic equipment according to the nominal working pressure.

But in reality, the connection between the contamination level and the filtration rating is not precise because the fluid conditions also depend on the features of the drive's design and various exploitation factors (Fig.2) [8], including the working pressure, which is usually very different from the nominal. The latter explains the corresponding changes in predicted long life parameters of hydraulic equipment (Fig. 3).

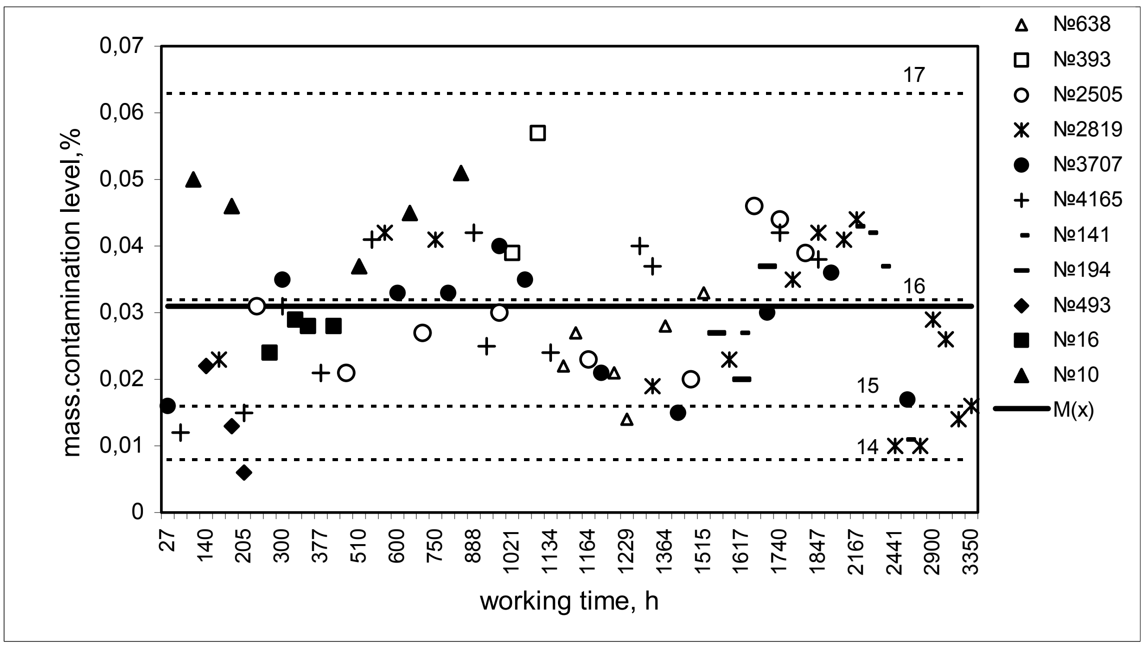


Fig. 2. Contamination level in 11 hydraulic shovels of the same model equipped with identical filtration systems (M_x – mathematic expectance).

So, it is appropriate to define the requirements for the fluid purification based on the desirable parameters of reliability applied to hydraulic components. After clarifying the corresponding filtration system price, it is possible to either accept it or change the initial demands.

In general, it is clear (Fig.1) that operating cost of mobile machines decreases inversely proportional to the fluid contamination level while, simultaneously, the filtration cost goes up.

That is why the extreme character of the "operating cost – contamination level" function is evident. Numeric analysis of the mentioned function in relation to the hydraulic drives of the shovel showed that economically optimal fluid contamination level for these machines is now about 90,000 – 100,000 particles (>10 mkm) per gallon (Fig 4.) In the long run, optimum displaces to the left due to the progress of filtration technology and corresponding to the

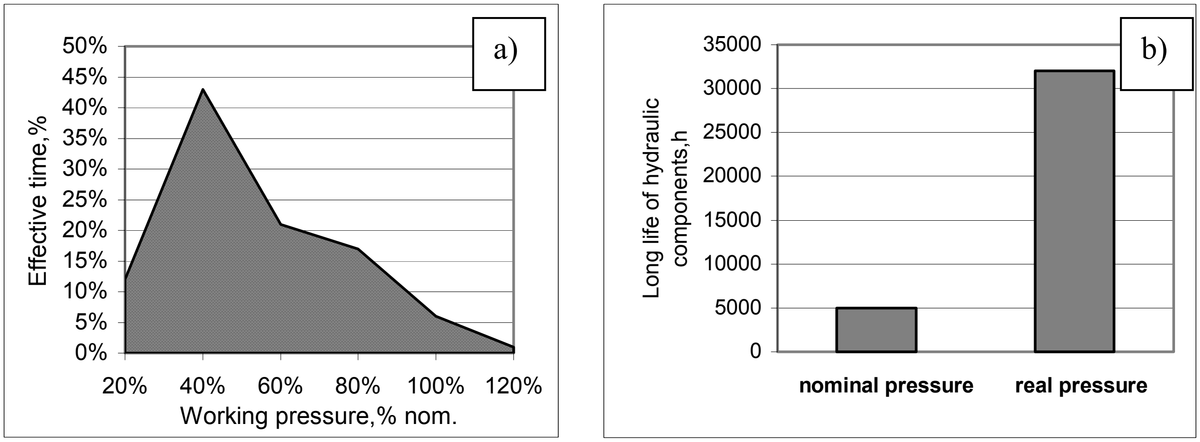


Fig. 3. Typical loading histogram of mobile machine hydraulic drive (a) and corresponding predicted long life of the main components (b)

relatively decreasing cost of filter media (see trend line). The mark (▼) shows predicted optimum for the year 2005.

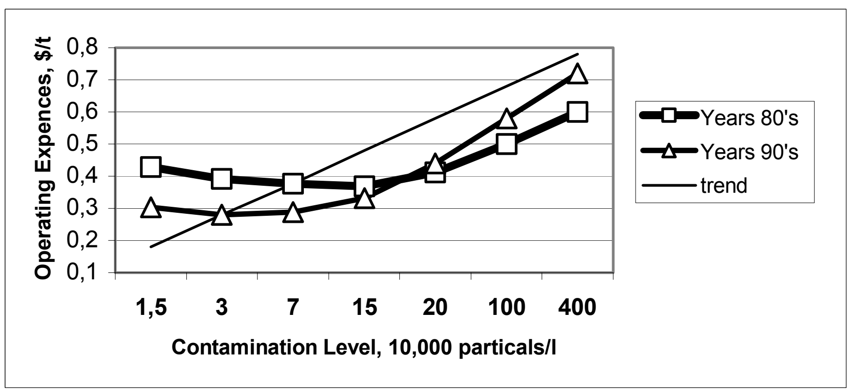


Fig.4. Operating expenses for excavation as a function of fluid contamination level.

From the economical point of view, it is possible to formalize the following demands for fluid purification applied to modern mobile machines hydraulic drives:

- Contamination level of 16/11 class (ISO 4406) that is near 30000 (particles >10 mkm)/l
- Maximum allowed particle size 35 mkm

There are some reasonable additional technical demands:

- Maximum allowed particle size 12 mkm for hydraulic circles control
- Maximum allowed particle size 7 mkm for proportional circles control

Certain features of mobile machines determine specific requirements for the development of filters in this direction. Such features include:

- Presence of several hydraulic circles with different demands on fluid purification

- Substantial (up to 300%) low frequency fluctuations of the fluid flow according to working cyclogram and high frequency (up to 7 Hz) fluctuation caused by load dynamics
- Change in fluid viscosity across a wide spectrum: in working process 10 – 15 times (from 20 sSt to 300 sSt) and during the startup - up to 250 times (5000 sSt)
- Significant size and mass limitations for units, including filters, simultaneously with the need to insure durability (as a rule, near 1000 maintenance-free hours)
- High contamination level of the air in a working zone
- Necessity of filter pressure drop minimization (usually limited to ΔP_{max} = 0,35 MPa) not only to fulfill the usual task of lowering energy loss, but also to accommodate the oil coolant in the return line of the hydraulic drive.

Filtration System Design

In general, filtration system can be defined as a combination of units suspended the contamination level in allowable limits during the exploitation time and placed in fluid flows. Based on this, the functions of filtration system are to:

- Let the fluid flow go through the filtration units while keeping differential pressure in acceptable limits
- Keep the system from contaminants penetration from the outside
- Remove contaminants from the fluid
- Remove particles held by filter from the system
- Keep cartridges and filter media from destruction
- Provide the control of the fluid quality and filtration equipment capability

Considering all the mentioned above functions and technical demands it is reasonable to take the scheme of filtration system design as shown on Fig 5.

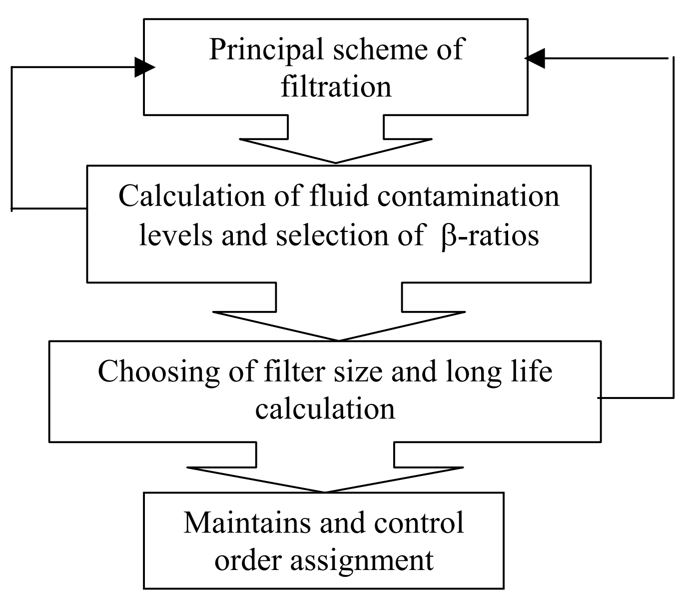


Fig. 5. Scheme of filtration system design.

Because the holding up of the particles is a statistic process, it is adequate to differentiate between two categories of filters:

- Working filters, suspending contamination level in tolerance limits, an efficiency criteria for which is a β-ratio
- Insurance filters, which hold particles of over limit size with 100% warranty.

To define a filtration scheme is to find particular placement points for working and insurance filters such that they keep contamination level and gravimetric curve in any hydraulic circle below tolerant average.

It is often considered that the contamination level of a hydraulic system in any given point is the same. Various field tests disprove this common opinion, showing that the particle concentration in certain hydraulic lines has 1,5 – 2 times difference (Fig. 6).

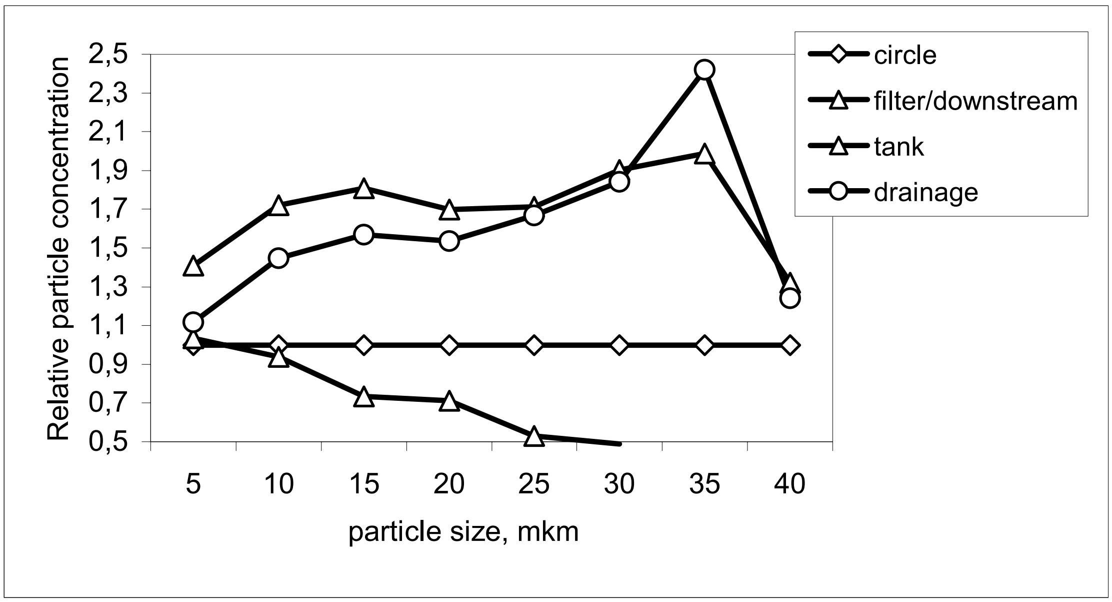


Fig.6. Contamination level in different hydraulic lines of a bucketwheel's drive (according to analysis of a fluid sample during 90 working days; relative error 17%).

Taking the above difference into account, it is necessary to introduce the concept of circulation ring. Let us call the circulation ring a part of the hydraulic system with such a fluid movement that there will always be a circulating particle, which may stay in this part for unlimited time.

Circulation ring is characterized by the presence of three kinds of particles: incoming, outcoming and circulating in the ring during any given period of time. There are two typical circulation rings in mobile machine hydraulic system:

- Tank with opened circles of working equipment drives & control system
- Closed circles with hydraulic motors for swing & travel drives.

These rings are connected to the hydraulic lines of valve 5 and pump 2, drainage lines of pump 3 and motor 4 (see Fig.7.) Fluid flowing in connection lines could be defined as an "exchange flows." In general, it is necessary to consider the following:

- Each circulation ring has to be equipped with its own filter

- All filters in the hydraulic system work jointly and each of them influence the contamination level in all circulation rings
- It is possible and necessary to maintain different contamination levels and gravimetric curves in different circulation rings
- It is reasonable to place insurance filters directly before sensitive hydraulic equipment
- It is advantageous to place filters on the ways of the particle penetration in hydraulic system and hydraulic lines with high contamination level
- It is always possible to increase fluid purification quality by using the additional ("off-line") pump and filter of small capacity, which will form special filtration circle
- It is important to place filters so that removal of oil-particle sediment is possible.

For the typical hydraulic drive (Fig.7), the filtration scheme with the placement of the filter according to the chart 1 is recommended.

Chart 1. Filtration scheme for typical mobile machine hydraulic drive

Point of placement	Filter type	Recommended parameters
A	Insurance	$B_5 = 20$ - $\beta_7 = 20$
B	Insurance	Absolute filtration rating 150 mkm
C	Working	Consider by calculation
D	Working	Consider by calculation
E	Insurance	$B_{10} = 20$ - $\beta_{12} = 20$

Calculation of Contamination Level in Hydraulic System Circles

The goal of the calculation is to define β-ratios for filters placed according to the chosen filtration scheme. The calculation is based on the contamination balance equations for any circulation ring:

$$Z_j = dC_j /dt + \{C_j * [\, \mathbf{\Sigma} Q_{jq} + Q_j * (\beta_j - 1)/\beta_j \,] - \mathbf{\Sigma} (C_q * Q_{qj} / \beta_{qj})\} / V_j \quad (1)$$

here: $\mathbf{Z_j}$ - particle penetration rate (PPR) as applies for " j " circulation ring, 1/s,

$\mathbf{C_j, C_q}$ - static contamination level as applies for "j", "q" circulation rings, 1/m

$\mathbf{Q_j, Q_{jq}, Q_{qj}}$ - exchange flows in " j " and between "j" and "q" circulation rings, m^3/s

$\mathbf{V_j}$ - fluid volume in "j" circulation ring, m^3

$\boldsymbol{\beta_j, \beta_{qj}}$ - BETA-ratios (ISO 4572) for filters in "j" ring and in "jq" line.

This system of linear differential equations shows variation of the particle concentration in circulation rings for hydraulic drive with random principal scheme. The miscalculation is defined by the inequality system:

$$D_c \leq (Z_j * V_j / Q_j) \quad (2)$$

Additional inaccuracy will occur because of the assumption that the initial fluid contamination level is zero. This inaccuracy is extremely small because the modern hydraulic systems are subjected to the start-up purification and, furthermore, the persistence of the initial contamination is not more than 50 - 100 working hours.

If the solution of the system (1) cannot give the desired contamination level with reasonable β-ratios, it is possible to change the filtration scheme, including the formation of the additional filtration circles. Iterations have to be repeated to receive desired solution.
It is important that the equations (1) can be solved for any gravimetric group of particles.

Long Life Calculation of Cartridge and Choosing the Filter Size

To specify filters, which are to be placed in the hydraulic system, a number of filtration parameters and design features, related to the operating factors of mobile machines (Chart 2), should be chosen.

Chart 2. Major parameters of filters

Filtration parameters	Design features
Nominal β – ratio	Maximum differential pressure
Nominal permeability	Method of cartridge's destroying prevention
Long life (Dirt capacity)	Method of downloading or cleaning of the cartridge
	Convenience of service for filters
	Mass and size of filters
	Durability for low temperatures
	Durability for dynamic loads

BETA- ratio calculated from system (1) is the base for filters' parameters determination. The problem is that the manufacturer gives us the nominal BETA value, founded by the laboratory test (for example, ISO 4572), which would never appear in real life conditions (Fig. 8.)

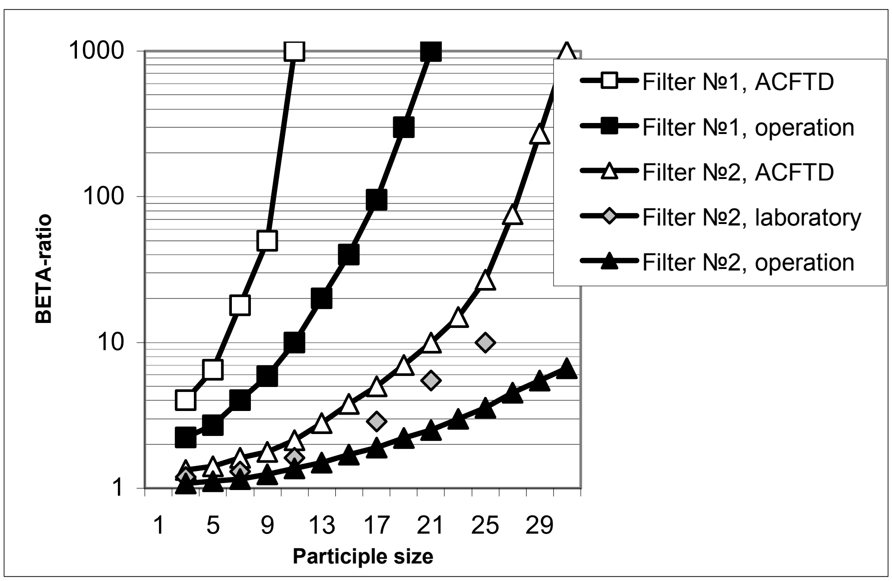


Fig. 8. BETA – ratios for shovel drive working filters tested with standard and real contaminant

The reasons for the disagreement between the two values are:

- Difference between standard and real contaminants (see curves Filter #2, ACFTD and Operation)

- Fluid flow dynamics and vibration negatively influences filtration efficiency (see curves Filter #2, Laboratory and Operation, worked out with identical real contaminant).

Hence, the “X” value should be chosen with the safety coefficient of 1.65 – 1.75. For example, if $\beta_{20} = 20$ were calculated from the equations (1), the designer would have to choose $\beta_{12} = 20$.
Filters’ long life has to be set up based on the desired maintains frequency of the drive. Because the mobile machines are used far from the service areas, it is impossible to change cartridges based on its real capability; for example, according to the signal of pressure sensor. Simultaneously, due to the high PPR, it is unacceptable to exploit the hydraulic drive without effective filter. So, as a rule, we have to provide a minimum of 1000 hours of effective long life for any filter.
If the customer wishes to buy a standard filter, the manufacturer will supply the information about the nominal dirt capacity according to the ISO 4572. In this case the size of the filter may be chosen based to the inequality:

$$G_j > R_j * Z_j \qquad (3)$$

or:

$$G_j = R_{fj} * \{[C_j * (\beta_j-1) * Q_j/\beta_j]\}$$
$$G_{qj} = Rfqj * \{[C_q *(\beta_{qj}-1) * Q_{qj}/\beta_{qj}]\} \qquad (4)$$

Here: G_j, G_{qj} – dirt capacity, m^3, R_j, R_{qj} – long life of filters in “j” ring and in “qj” line, s.
If there is no information about dirt capacity, it can be calculated based on the standard characteristics of cartridge and filter media using the equation:

$$G = H * m * \delta * K_{eff} [(1- (\Delta P_o / \Delta P_\tau)^{1/2}] \qquad (5)$$

Here: **H** – pore profile factor, which defines the irregularity of dust holdings in filter media, is calculated from [4] or chosen from Fig. 9, **m** – porosity of the media, %, δ - its thickness, m, $\mathbf{K_{eff}}$ – effective area factor, numerically equal to the ratio of pressure drop on pure filter media and cartridge with the same surface area (for the ideal construction of the filter cartridge K_{eff} = 1), μ - fluid viscosity, Ps, $\mathbf{\Delta P_o}$ и $\mathbf{\Delta P_\tau}$ – initial and maximum differential pressure, Pa.

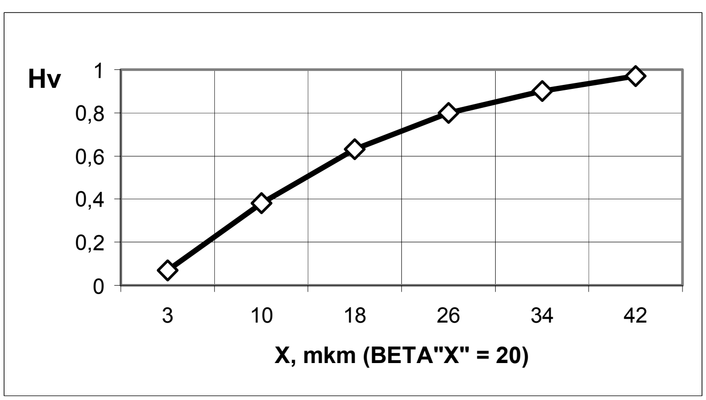


Fig. 9. Pore profile factor as a function of β-ratio.

From the past experience, we recommend an empiric way of choosing a filter's size. Usually, if

$$\Delta P_o / \Delta P_\tau < 0{,}05 \qquad (6)$$

cartridge has a long life close to the optimal. Unfortunately, sometimes, this principle is not applicable due to the dimensional limits.
Although the size of the filter is chosen according to the long life criteria, the check for permeability is necessary. Cartridge has to be permeable enough to work with the flow, obtained from the following equation:

$$Q_f = W_p * C_{ss} * C_{ds} \leq 4.5 * W_p \qquad (7)$$

where $\mathbf{W_p}$ is the pump flow capacity; $\mathbf{C_{ss}}$, $\mathbf{C_{ds}}$ are, respectively, the static and dynamic coefficients of the amplitude of modulation in the volume of the fluid flow.
In addition, the possible viscosity fluctuations have to be taken into account. Thus, the following changes in calculation of the drop pressure:
In the viscosity range of $500 \leq \nu \leq 4000$ sSt $\quad \Delta P_\nu = \Delta P_{30} * \nu/30 * \exp(-\nu/2300)$
In the viscosity range of $4000 \leq \nu \leq 5000$ sSt $\quad \Delta P_\nu = \Delta P_{30} * \nu/130$
If the filters, chosen to meet filtration criteria, cannot fit mass-size limitations, the filtration scheme has to be changed.

Particle Penetration Rate and Special Features of Gravimetric Curve

Particle Penetration Rate (PPR) is a vital initial data for the filter's calculation. In addition, due to the enormous variation of mobile machine operation conditions, the possibility to work out the authentic numeric information was usually put into doubt.
But taking into account that:

- Air ("breath") filters have a certain efficiency;
- Wear intensity and the level of technological contaminations are roughly equal for most of the industrial hydraulic drives
- Quality of supplied fluid is more or less the same, especially while using standard filling equipment,

there was an attempt to value a general numbers of PPR for mobile machine hydraulic drives. Experimental study of 97 mining and construction machines based on fluid samples analysis as well as on the direct measurement by weighting precipitation left in purification equipment, tank and hydro components, showed that PPR value fluctuation is less than expected (Chart 3).
It is important to notice, that the above results have good correspondence to the theoretical analysis of contaminant source potential and real long life of filter.
Based on the experimental results, the approximated dependence of PPR as a function of fluid contamination level could be suggested (Fig. 10). The physical meaning of this function is in decreasing the wear of the hydraulic components while improving the purification level. This is also explained by the fact that the tangent of gravimetric curve changes simultaneously with the contamination level (Fig. 11).

Chart 3. Particle Penetration Rate applied to the mobile machines hydraulic drives (contamination level 17/12 ISO4406, aggregates long life 5000 – 7000 h)

Particle Penetration Rate	Particle quantity, %, by size, mkm						Total particle quantity	
	10-15	15-20	20-25	25-30	30-40	40-50	Math. expectation 1/(l*min)	Variation ratio %
Tank	60	27	5	4,5	3,2	1,3	$1{,}1*10^5$	28
Circle	13,3	16	34,6	18,6	9	8	$0{,}34*10^5$	48
System	51	25	10	7	4,5	2,5	$1{,}35*10^5$	31
System: mass. PPR, % fluid mass							0,018	33

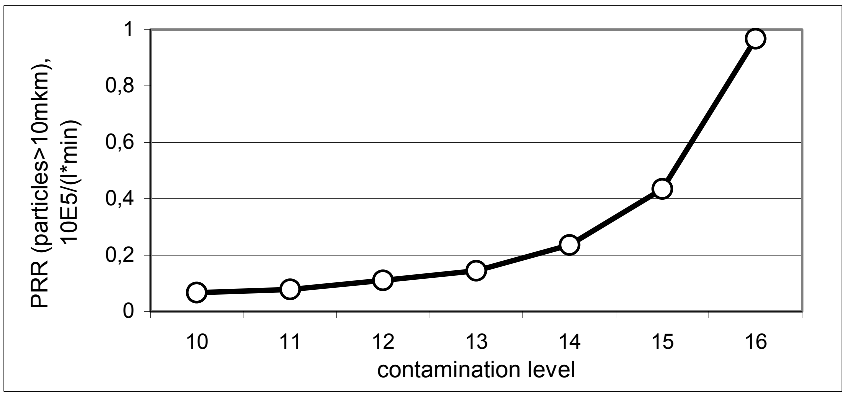


Fig. 10. Particle Penetration rate (PPR) as a function of the fluid contamination level

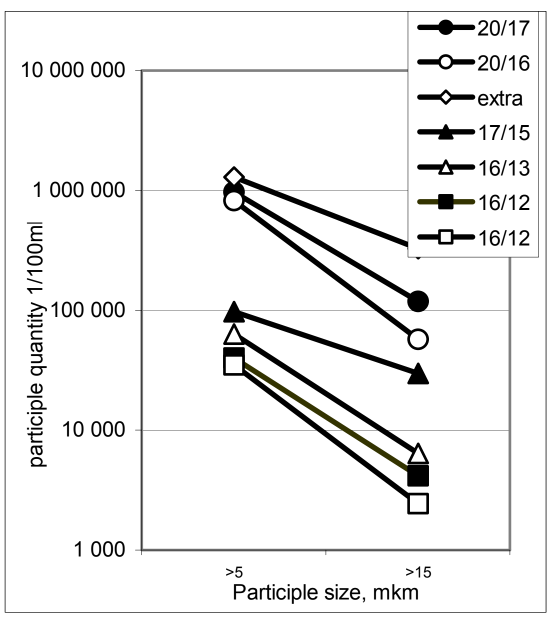


Fig.11. Typical gravimetric curves for hydraulic shovel power drives ("extra – filling barrel, the rest – hydraulic systems; average data from 49 experimental series)

Filter Cartridge Evolution

During the last 30 years, various new designs of filter cartridges were proposed to fulfill the advantages and smooth out the defects of the particular filter media. Nevertheless the main design is still based on the star-shaped filter curtain, and we can assume that in future it will not lose its dominant position. Up till now, cellulose and glass paper are leading the market but the gradual increase of nonwoven media use seems to be especially important tendency (fig.12.)

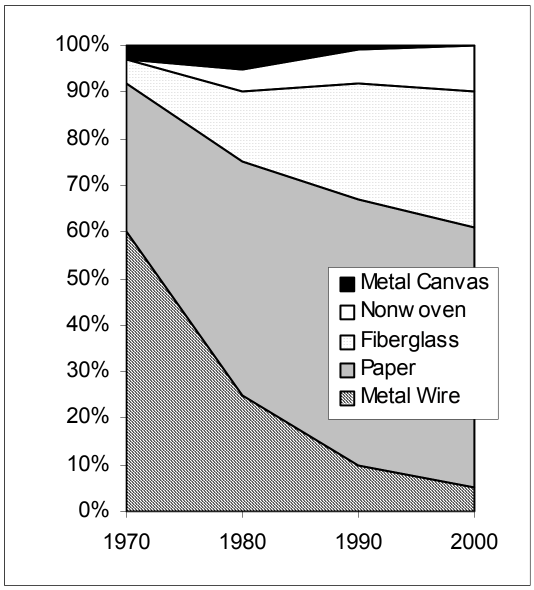


Fig. 12. Range of use of different media in hydraulic drive cartridge application

The important direction towards the improvement of the filters is the uprising of their exploitative durability based on sequential filtration effects. Although the direction is not recent, it substantially developed especially in the last decade, based on combinations of purifiers of distinct physical nature (for example the combination of separator/filter or hydrodynamic gravity system/filter) in one constructive unit. As to cartridges, the said direction is represented by samples with a multilayer filter curtain. The decrease in price of the glass paper and nonwoven allows us to predict a certain progress in this tendency already by the year 2005 (chart 4.) The requirements for the alternation of the filtration thickness due to the dependence of the layer (elementary section) location for the fluid flow is determined by the predictability studying of the process of deepening filtration and has to correspond with the optimization curve [6], Fig 13.

It is important to create a filter ensuring curtain stiffness in the whole range of working pressure drop (fig. 14) provoked the achievement of required operational life magnitude. This goal can be accomplished by curtain reinforcement with glue compositions, wire meshes, different types of downlayers etc. This direction of cartridge design development can be expected to be the

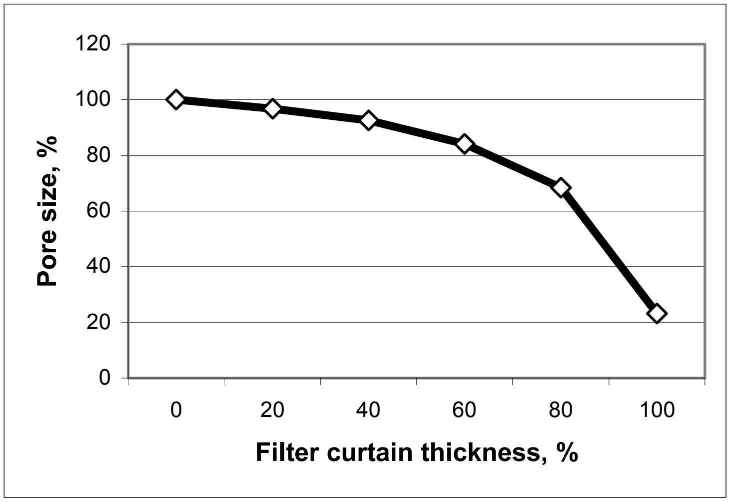


Fig. 13. The optimal size of the pore as a function of the layer (elementary section) location (for 90% efficiency curtain)

primary in the close future along with simplification and price reduction of structural elements (for example, extrusive plastic nets).

Chart 4. Contemporary demands and development prognosis for mobile machine filter media

Filter	Point on the scheme (fig.7)	Year	Burst Strength kPa	Air permeability mm/s *	Max. pore size mkm	X mkm **
Insurance (proportional control)	A	2000	250-350	30 –100	10 - 40	3 – 12
		2005	300-400	75 - 150	7 - 20	2 - 7
Insurance (hydraulic control)	A	2000	250-350	30 –100	25 - 45	7 – 15
		2005	300-400	75 - 150	15 - 30	5 - 10
Insurance	B	2000	250-350	600-1000	90-150	30-45
		2005	250-350	1000-1500	70-100	25-35
Working (in line)	C	2000	300-400	350-800	40-90	12-30
		2005	350-450	500-1000	25-60	8-20
Working (in line)	F	2000	300-400	250-600	55-70	17-25
		2005	350-450	400-900	20-40	7-15
Working (additional)	D	2000	300-400	70-300	35-60	10-20
		2005	350-450	150-400	20 - 45	7 – 15
Working Air (“breathing”)	E	2000	180-250	600-1000	90-110	30-40
		2005	180-250	600-1000	25-60	8-20
Working (Filling unit)	G	2000	180-250	600-1000	90-110	30-40
		2005	180-250	600-1000	30-60	10-20

Comment: * - for differential pressure 200 Пa
** - according to $\beta_x = 20$

The main issue in the development of filters for mobile machines is to increase their long life. Therefore, using new materials with high permeability, we should not minimize the size of the filter. It is appropriate to use all the allowed mass-dimensional limits to increase the area of the filter curtain. As a result the long life of filter will increase more rapidly (Fig. 15). This effect has a greater influence on liquid than on air filters (compare to curve "Air cartridge" where points 1,2,3 had been interpolated using data [7]). The physical nature of the difference is based on the fact that for hydraulic cartridges, depth filtration is more prevailing than for air ones. Also, we have to consider that the increase in dirt capacity has a greater effect on fine filters.

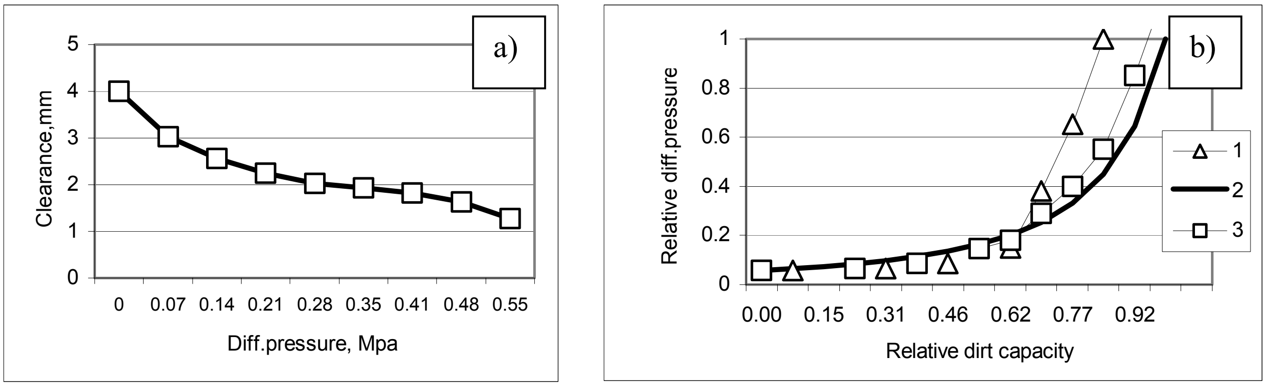


Fig.14. Clearance of pleats as a fiction of differential pressure (a); Dirt capacity as a function of filter curtain stiffness (b): 1- standard stiffness, 3-high stiffness, 2-theoretical curve

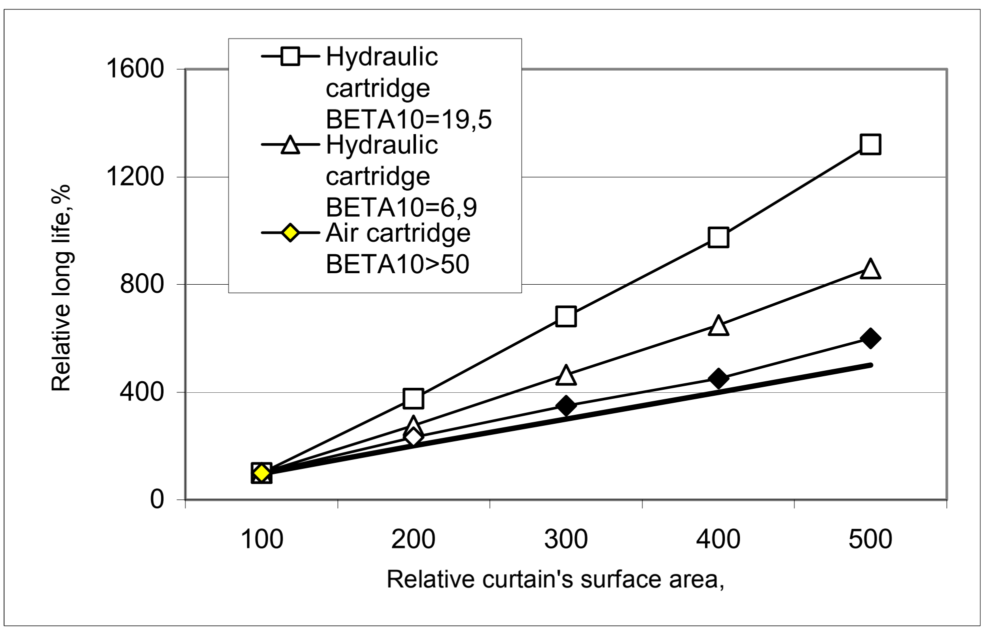


Fig.15. Cartridge long life as a function of filter curtain's surface area

The additional rising of relative characteristics of cartridges could be achieved by using the method of optimizing "depth-number" parameters of curtain pleats [4].

Designing filter housing, it is necessary to consider the following:

- Fluctuant loading and working cycle interruptions cause sedimentation of contaminants held by the surface of the curtain. When the system unloads, the particles "drop down" to the lower part of housing due to the low friction in oil surrounding. It is experimentally proven that by forming special sedimentation zone, which will not allow particles to be "shaken up," the long life of cartridges can be increased up to 15-40%

- Taking into account the fluid flow dynamics, it is necessary to form the incoming housing channel securing cartridge curtain from hydrodynamic destruction
- Static and dynamic characteristic of bypass valve have to be designed considering cyclogram and flow fluctuations. Also, because the viscosity may change, the use of filters without bypass valves highly undesirable.

Acknowledgement

The author thanks Dr. A. Gozman who has provided significant results of filter media market analysis. He also wishes to express the appreciation to Alexandra & Elena Brodski for their help in the preparation of this publication

References

1. Brodski G. Hydraulic mining bucketwheels reliability increasing by the development of working fluid conditioning systems. Moscow, 1986.
2. Basheva A. Reliability research for construction shovels hydraulic equipment. Moscow, MADI, ref. #0180035504, 1987.
3. Drecsler P., Faatz H., Faiht F. Designing and building of hydraulic plants. Lor-am-Main, 1988
4. Brodski G., Gozman A. Filter Media Selection in the Designing of Cartridge Filters for the Purification of Varying Viscosity hydraulic Fluids. Advances in Filtration & Separation Technology, Volume 13a, p. 884-892
5. Brodski G., Vereskunov V. Effective methods of working fluid sample testing in hydraulic systems. Journal: World Mining Industry, #3, 1997
6. Brodski G. Current Development of Filter Media & Cartridges for Automotive & hydraulic Systems. Dusseldorff Europe Filtration Congress. Filtech'99, p. H35-H48.
7. Murphy W.F. The effect of surface area on dust capacity. Dixie Chapter of AFS, October 23, 1997.
8. Alekseev V., Marchenco C., Odintzov V. Fluid Purification classes in Eo-3322A shovels. Krasnoyarsk, ref. #EK-2/505-81, 1982