

Off-line and bypass filtration solutions for the hydraulic drives of mobile machines

The choice of the principal scheme for the filtration system generates most controversial discussions during the design stage. There exist a significant number of filter placements and each placement has its advantages and disadvantages [1] defined primarily by design particularities of the purifiers. Nevertheless, in view of the continuously increasing demands to the industrial purity, one can reasonably talk about the continuous amplification in filters' effectiveness. However, because of the typical for mobile machines mass-dimensional limitations, it is often difficult to apply highly effective filters to the full flow (Fig.1.) Given the specific characteristics of the real contaminant, which is not uniform and contains a significant number of small particles (Fig.2. Here and further, the diagrams are based on the data obtained from the research of mining and construction machines), the difficulties of application of full flow purifiers become even greater (see curves marked "Mass" on Fig.1). Therefore, even in the 1980ies, bypass filters were being used in hydraulic and oil drive systems of mobile machines [5]. One of the first examples of their application is a shovel Hitachi UH-801, in which a parallel filter with $\beta_3 = 20$ was used. Until now, in most cases bypass filters are employed together with full flow ones. Usually, the following relationships of nominal flow magnitudes and β -coefficients are used:

$$\begin{aligned} Q_{F2} &= 0.05 \dots 0.10 * Q_{F1} \\ \beta_{F2} &= 5 \dots 15 * \beta_{F1} \end{aligned}$$

Here and further index "F1" applies to full flow, "F2" to bypass filter

At the end of 1990ies, new materials, allowing for the implementation of the combination of high dirt-capacity and β -ratio with acceptable cost, appeared. They opened new opportunities for the development and the optimization of the parameters of bypass filtration systems. First of all, since the retention of contamination particles is a statistical process, the use of highly effective bypass filter may, in certain cases, eliminate the necessity of the full flow filter. Applying equations for contamination balance [2] and taking into account the real values of particle penetration intensity for modern high-pressure systems (Fig.3), one can show that the bypass filtration only is often sufficient for creating the liquid of required purity (Fig.4). Therefore, when designing a filtration system, it is technically possible and economically reasonable to utilize a combination of two types of filters, each solving a principally distinct task:

- Bypass (working) filters employed to hold the majority of contaminants flowing into the system and to maintain the purity of the liquid at the required level. Apart from the β -ratio, the most important parameter of this working filter is dirt capacity.
- Full flow (insurance) filters, which are designed to catch (with 100% probability) the particles larger than maximally allowable. There are very few of those particles when the machine is working within its standard regimes, since the ratio between filtration efficiencies of insurance and working filters is usually larger than 2:1. Therefore, apart from the β -ratio, the most important parameter of this filter is its flow rate.

Because for contemporary machines the costs of liquid purification, in the general balance of exploitation expenses, are significant (Fig.5), while designing a filtration system one should use the criterion of the lowest cost of liquid purification in an hour of equipment work at an acceptable service schedule.

In many cases and, primarily, in marketing of the new filtration technologies, it is extremely important to be able to appraise the economical parameters quantitatively. It is suggested to compute the general cost of liquid purification (E_{EF}) as a sum of:

- cost of filtration system (Z_{fs});
- cost of service expressed as:

$$E_{FU} = \sum [(A_z * E_L + E_{SPZ} + \Delta V_f * E_f) / R_{zdsr}] |_{z=1 \dots Z}$$

Here, A_z , E_{SPZ} , ΔV_f – is the labor consumption for servicing, the cost of parts, the losses of working fluid during the servicing of z- filter, E_L , E_f – cost of a unit of time or personnel's work and cost of the unit of volume of working fluid;

- energy consumption expenses (W_{FU}).

The filter's energy consumption expressed in power units (Watts) increases with the change of pressure on it as it gets dirtier, and can be shown as:

$$W_z = \Delta P_{eqz} * Q_z,$$

Where ΔP_{eqz} is the equivalent differential pressure on filter z in a period R_z .
Since the change of pressure on the filter housing remains constant during its whole service period,

$$W_z = [\Delta P_{z0} * (1 - a_{ef}) + \Delta P_{eqfz}] * Q_z,$$

Where a_{ef} is a coefficient of the effectiveness of the filter housing, quantitatively equal to the ratio of differential pressure on the filter element and filter at nominal fluid flow and viscosity.

Based on the mathematical description of filter's lifespan [3], the working time of a filter cartridge can be shown as:

$$t = F_z * K_G * H_{vz} * k_{effz} * \varepsilon_z * \delta_z / (\beta_{mz} * C_z * Q_z) * [1 - (\Delta P_{z0} / \Delta P_{zt})^{1/2}]$$

or

$$t = \alpha_{11} * [1 - (\Delta P_{z0} / \Delta P_{zt})^{1/2}],$$

where magnitude α_{11} may be found from the boundary conditions $\Delta P_{zt} = \Delta P_{zmax}$, $t = R_{zdsr}$ described as:

$$\alpha_{11} = R_{zdsr} / [1 - (\Delta P_{z0} / \Delta P_{zmax})^{1/2}]$$

Then,

$$\Delta P_{zt} = \Delta P_{z0} / (1 - t / \alpha_{11})^2$$

It is evident that

$$\Delta P_{eqfz} = \Delta P_{z0} * \int (1 / (1 - t / \alpha_{11})^2) dt$$

The shown integral is calculated as [6]

$$\Delta P_{z0} * \int (1 / (1 - t / \alpha_{11})^2) dt = \alpha_{11}^2 * \Delta P_{z0} / (\alpha_{11} - t)$$

Then, on the closed interval $[0, R_{zdsr}]$ after the derivations one will see that

$$\Delta P_{eqfz} = [(\Delta P_{z0} * \Delta P_{zmax})^{1/2} - \Delta P_{z0}] / [1 - (\Delta P_{z0} / \Delta P_{zmax})^{1/2}]$$

So, the average energy consumption of a filtration unit during the time of service is defined as:

$$W_{FU} = \Sigma [\Delta P_{z0} * (1 - a_{ef}) + \Delta P_{eqfz}] * Q_z |_{z=1...Z}$$

Using the equations given above, the economical reasons for choosing the parameters of filtration systems can be taken into account. For instance, the analysis of the single-circuit system shows that filter with $\beta_{15} = 12$ at $Q/V=0.19$ is an optimal one to use, since this combination of filtration and energy characteristics assures the better size and price (Fig.6).

When calculating the economical effectiveness of a filtration system, a comparison is made between the magnitude of E_{EF} and the revenues obtained from the exploitation of a mobile machine, taking into account the increase in the machine's reliability and productivity, as well as the decrease in the use of replacement parts and materials. In particular, the following articles can be the sources of the economical effectiveness of filtration systems [4]:

- increase of the lifespan of the main aggregates of the drive (engine, hydraulic system elements, etc.);
- raise in productivity of the technology due to the increase in EER of the drive;
- amplification in technical availability ratio;
- 15-25% decrease in fuel, motor oil and hydraulic fluid expenditure;
- increase in service intervals and service times of working fluids;
- decrease of servicing and repairs expenditures.

It is interesting to note that real opportunities for introduction of the economically practical bypass systems appeared relatively recently (Fig.7 and 8, curves Z_{fs}). It is necessary to pay attention to the accompanying decrease in energy consumption needed for liquid purification, which represent a significant percentage of exploitation expenses of filtration systems (see curves W_{fs}/Z_{fs} on Fig.8).

Further development of the idea of a bypass liquid purification includes the application of the so-called off-line filtration devices, which allow for the formation of an independent circulation and therefore provide for the purification of the liquid even when the main system is not working. Consequently, the off-line filter can be serviced on a flexible schedule and will not be dependent on the workload of the equipment.

The use of the off-line devices is very effective in the development of filtration systems for new machines, as well as in the modernization of exploitation technology in cases when the existing filters cannot handle the real workload and cannot guarantee the realization of a necessary granulometric curve. For instance, the portable filtration unit PFU-10m, with the glass paper filter with $\beta_{10}=100$, guarantees the effective capture of the majority of particles larger than 3 microns in one working shift (6 hours). In order to maintain the necessary level of purity (no worse than 16/13 level) in the hydraulic system of the shovel with the bucket of 1 m³ (hydraulic system volume up to 1200 liters) using only one insurance filter with $\beta_{20}=2$, it is sufficient to use PFU-10m once or twice a month, depending on the specifics of exploitation.

The assembly of the off-line filtration units usually requires only insignificant modernization and allows achieving the desired results (Fig.9) with minimal expenditures. Mobile off-line units can be effectively used not only as a part of the filtration system but also independently, for pre-launch and post-repair fluid service as well as refueling. For instance, sudden equipment refusals related to the fluid leaks are rather frequent in hydraulic systems of mobile machines. The elimination of such refusals in field conditions leads to the contamination of the hydraulic system with a large number of particles and, consequently, to the fast strain on the filters. Such an occurrence can lead to the premature breakage of the filters, exponential increase of contaminants and to further equipment refusals. Such a process, once initiated, results in the loss of quality of a hydraulic drive in the time period of several hundreds of hours. To prevent of this, the application of the off-line filtration device for post-repair cleanup is extremely profitable.

1. Rausch, K. Which filters are most effective? Hydraulics & pneumatics, February 2002, p. 31-33
2. Fitch E.C. Fluid contamination control. FES Inc., OK, USA, 1988 – 433 p.
3. Brodski, G.S. Filters and filtration systems for mobile machines. Mining Industry, 2004 – p. 360.
4. Brodski G.S. Effectiveness of the contemporary filtration technologies for exploitation of mining machines. Mining Industry, №5, 2002, p.2-6.
5. Brodski, G.S., Suhorukov, A.N., Zuev, V.I., Basheva, A.A. Results of testing of filter and filtration elements for SDM. Building and Road Machines, №11-12, 1992, p.7 –9.
6. Dwait G.B. Integral calculus, Moscow, 1983

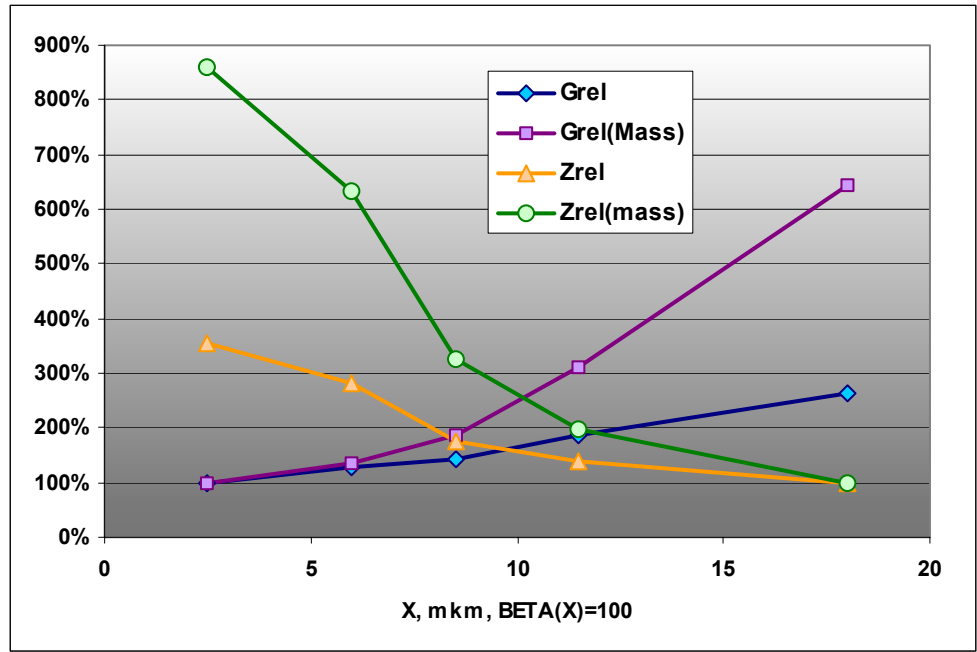


Fig 1. Relative dimensional and cost indicators of the recent high-pressure hydraulic filters. **Grel, Zrel** – relative size and cost characteristics, respectively. **Grel(Mass), Zrel(Mass)** – same, with the consideration of granulometry of the contaminant.

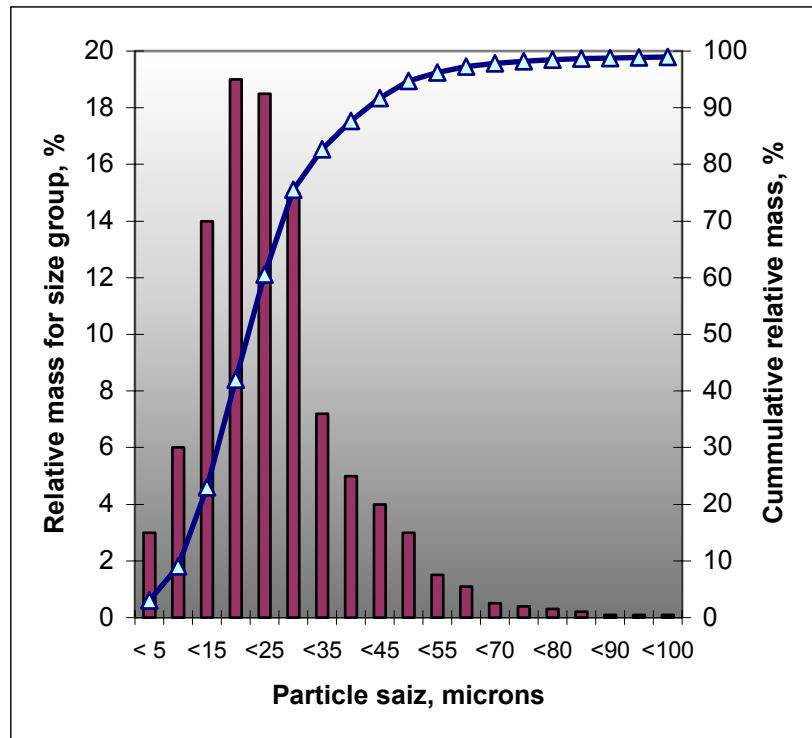


Fig. 2a. Pareto Diagram for relative mass of contamination particles.

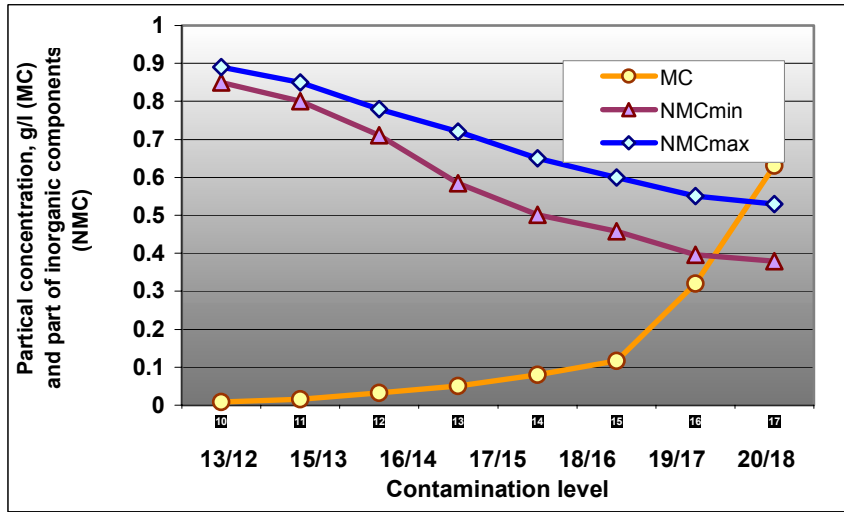


Fig. 2b. Part of inorganic components in the general mass of the contaminant.

PFU-10m

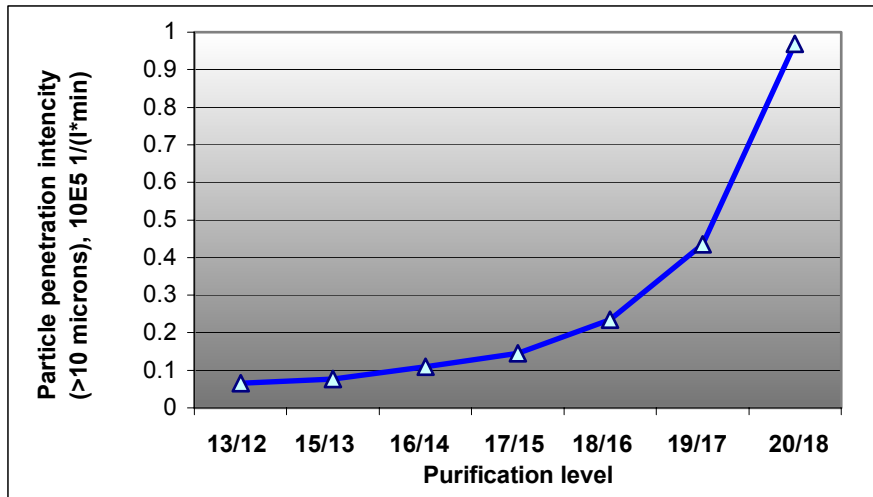


Fig. 3. Particle penetration intensity depending on contamination level (ISO4406).

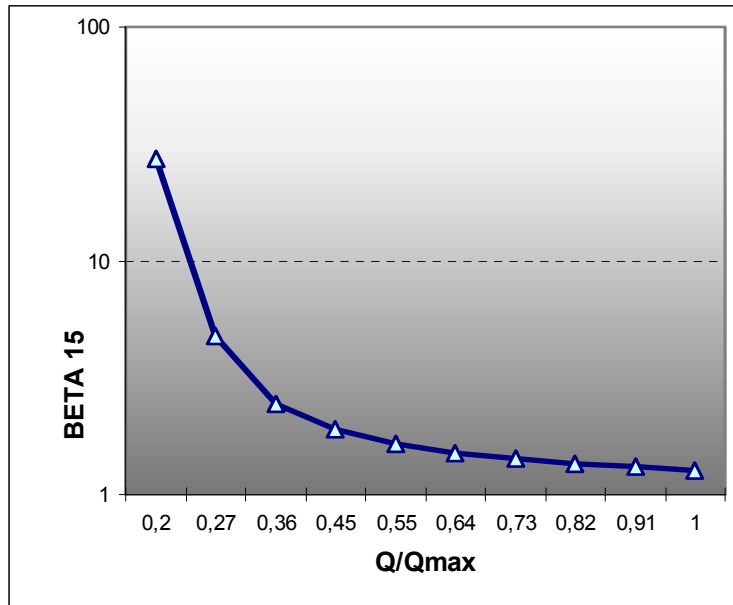


Fig. 4. β_{15} - ratio required for providing the contamination level of 16/13 from the relative magnitude of the flow through the filter. The unit is assumed to be the maximum pump output.

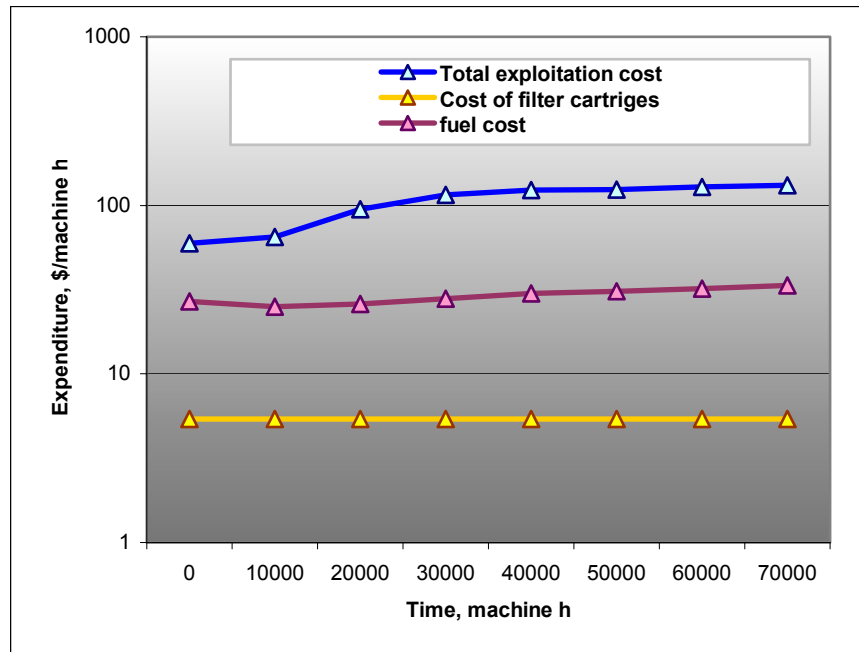


Fig. 5. The expenditure for the exploitation of the shovel with the bucket of 15 m³ (1200 kW).

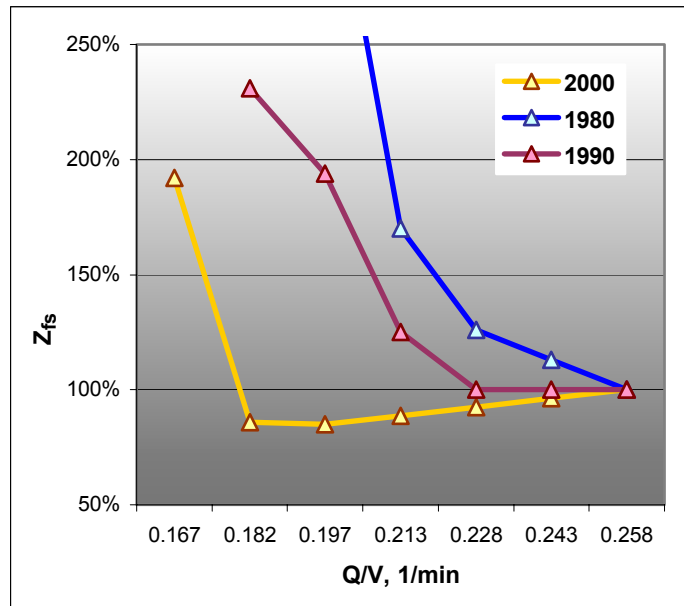


Fig. 6. Dependence of the surface area of the filter (in relative units) and expenses for liquid purification in a single-circuit hydraulic system from purification ratio (Q -flow through the filter, V -system volume, β_{15} depends from purification ratio as shown on Fig.4).

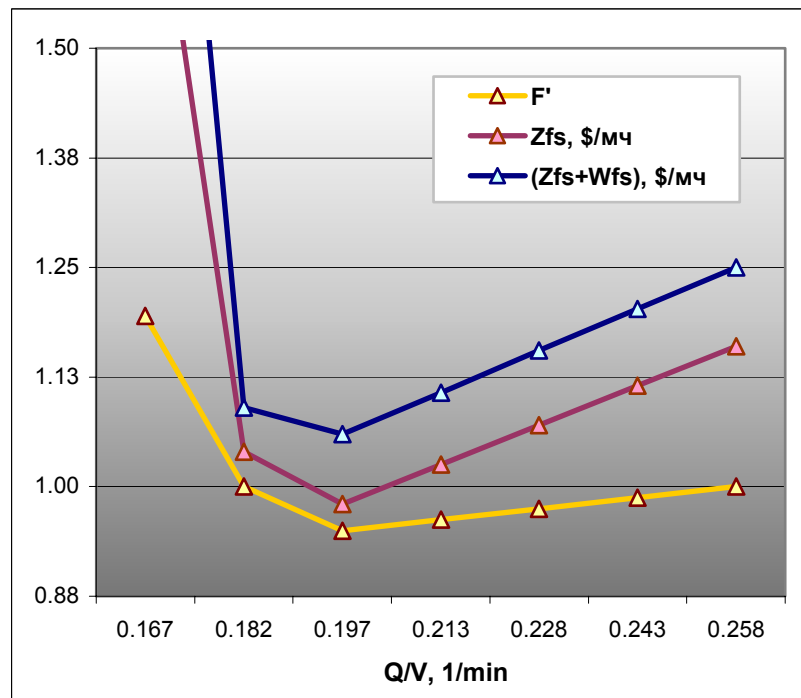


Fig. 7. Dependence of the expenses for liquid purification in a single-circuit hydraulic system from purification ratio using various filtration materials:
2000 – modern glass papers;
1990 – cellulose papers of 1990ies;
1980 - cellulose papers of 1980ies.

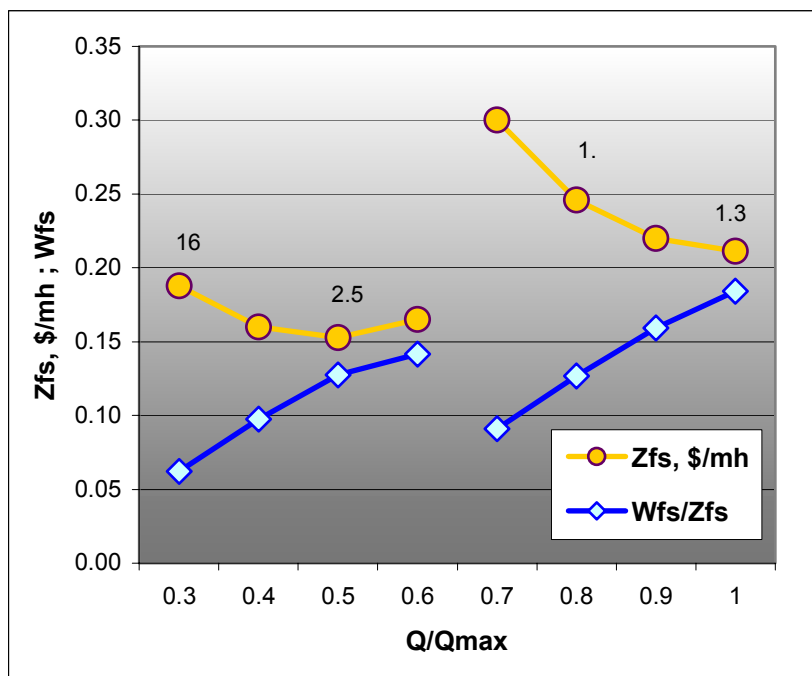


Fig. 8. Dependence of fluid purification expenditures in a single-circuit hydraulic system ($Q_{max}=425$ l/min, $V=1275$ l) from the type of the filter used (magnitudes of β_{10} are shown on the field of the picture, points “1.3” and “1.5” correspond to the cellulose filter cartridges produced in 1990ies and points “2.5” and “16” correspond to glass fiber cartridges produced in 1990ies).

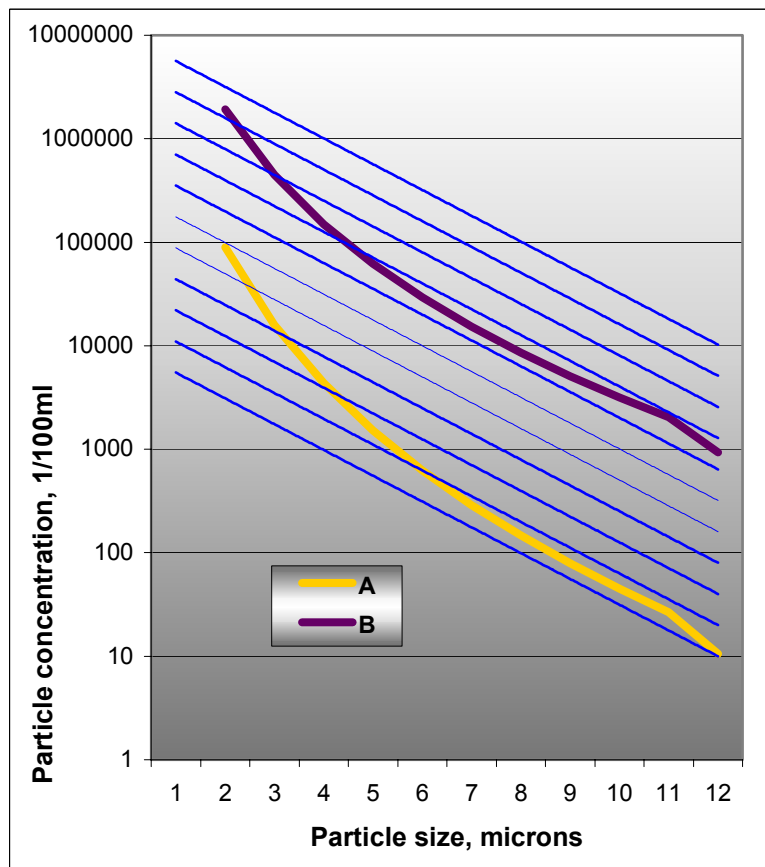


Fig. 9. Averaged granulometric curve for working liquids of hydraulic drives of EO-3322 and EO-4121 backhoes:

- A- with conventional filtration system;
- B- with additional off-line filtration device $\beta_5 = 100$.