

Assessment of factors contributing to failures in hydraulic systems of mining excavators

Nabijon Abduazizov¹ , Javokhir Toshov^{2,3} , Lazzat Abdiyeva⁴ , Khuangan Nurbol⁴ ,
Akbar Zhuraev¹ , Bakhtiyor Baratov² , Rabatuly Mukhammedrakhym^{4*} 

¹ Navoi State University of Mining and Technology, Navoi, Uzbekistan

² Tashkent State Technical University, Tashkent, Uzbekistan

³ University of Tashkent for Applied Sciences, Tashkent, Uzbekistan

⁴ Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan

*Corresponding author: e-mail mukhammedrakhym@gmail.com

Abstract

Purpose. To identify and quantify the main factors causing failures in hydraulic systems of open-pit excavators, with particular emphasis on the influence of the cleanliness and physicochemical condition of the working fluid on the reliability and service life of hydraulic units.

Methods. The study is based on an integrated approach that includes an analytical generalization of literature and operational data on hydraulic system failures, determination of working fluid cleanliness class using a Luvatech S41 particle counter, and physicochemical characterization of fluids by infrared spectroscopy, X-ray fluorescence analysis, visual assessment, and microscopy. The effect of contamination on the service life of hydraulic units was additionally evaluated using a calculation model that accounts for particle concentration and particle-size distribution.

Findings. It was established that working fluid contamination accounts for approximately 70% of hydraulic system failures. Particle count analysis showed a progressive increase in contamination with increasing operating time, with the most pronounced growth observed for the 2-5 and 5-10 μm fractions, indicating intensified abrasive wear in the hydraulic system. X-ray fluorescence analysis revealed an increase in SiO_2 content from 88.740 to 93.474%, indicating contamination of the working fluid by silicon-bearing abrasive particles. Infrared spectroscopy identified structural changes in the working fluid and the appearance of additional absorption bands associated with its chemical degradation during operation. Microscopic examination of used oil confirmed the presence of solid impurities. An economically and technically justified working fluid cleanliness level corresponding to ISO 4406 class 15/13 was determined, thereby improving reliability and reducing operating costs.

Originality. For the first time, an integrated approach is applied, combining particle-size analysis, physicochemical diagnostics of the working fluid, and assessment of hydraulic unit life to establish the relationship between working-fluid cleanliness, contamination characteristics, and hydraulic-system reliability under real operating conditions.

Practical implications. The results obtained can be used to improve filtration systems, optimize maintenance strategies, and support early diagnostics and predictive maintenance of hydraulic equipment at mining enterprises.

Keywords: hydraulic excavator; hydraulic system; working fluid; contamination; failures; infrared spectroscopy; X-ray fluorescence analysis

1. Introduction

In recent years, rapid economic development, population growth, and expanding industrial production have substantially increased the demand for mineral resources. In particular, the need for construction materials, ferrous and non-ferrous metals, and energy resources has grown sharply [1]. The production of electric vehicles, along with the development of renewable energy and digital technologies, has further increased demand for strategic raw materials such as copper, lithium, nickel, and cobalt. At the same time, the demand for gold has a particular strategic significance. Under current conditions, gold is regarded not only as a raw

material for jewelry production but also as an investment asset and an important component of central bank reserves. The growing interest in gold amid geopolitical instability and financial risks calls for increased production. This trend, in turn, calls for higher output in the mining industry and the development of new large-scale deposits [2], [3].

The increasing demand for mineral resources is accompanied not only by the intensification of extraction and raw material processing, but also by a wider range of technological and environmental challenges related to the management of technogenic raw materials, by-products, and waste generated by mining and metallurgical production [4]-[7]. In mo-

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modern mining regions, this is reflected in the need for a more detailed consideration of the mineral composition of technogenic materials, impurity components, and the conditions for their subsequent processing or recovery [8]-[12]. Processes involving the separation, sorption, and transformation of impurities in technological systems are also becoming increasingly important, both for resource conservation and for reducing associated technogenic impacts [13], [14].

In mining and mineral-processing operations, solid-phase impurities, secondary products formed by interactions between the medium and the materials, and dispersed components play a particularly important role, as they can alter the properties of operating systems and accelerate equipment wear [15]. In this context, the chemical nature of impurities, their phase state, and their behavior in the technological medium are of considerable importance. This is supported by studies dealing with the composition of oxygen-containing compounds, the sulfidation of concentrates, and the processing of complex mineral raw materials [16]. The formation of stable contaminating components and their influence on the properties of the medium should also be taken into account when assessing the operational stability of equipment operating under complex mining and technological conditions [17].

Open-pit methods mine most modern gold deposits, and these operations are typically large-scale and deep, often reaching depths of several hundred meters [18]. The need to process low-grade gold ores further increases production volumes, thereby increasing the demand for high-capacity excavators and other mining equipment [19]. At the same time, the high hardness and abrasiveness of rocks in gold ore deposits create additional technical challenges for hydraulic equipment.

At modern mining enterprises, operating hydraulic excavators under harsh environmental conditions requires rapid maintenance and repair of hydraulic systems. One effective way to ensure the technological reliability of such machines is to identify the main causes of failures and subsequently implement a comprehensive program of scheduled preventive maintenance.

The relevance of identifying and studying contaminants that initiate wear in hydraulic equipment components is widely recognized internationally. Highly efficient hydraulic system operation under complex mining and geological conditions can be achieved by maintaining optimal working-fluid properties, enabling maximum productivity with minimum operating costs. More broadly, improving the efficiency of mining and transport-technological equipment is regarded as an important direction in the development of modern mining production, including the optimization of operating modes, braking systems, and logistics-related technological schemes [20], [21].

Under current conditions, improving the efficiency of mining industrial systems is increasingly associated not only with equipment modernization and the reduction of structural material consumption, but also with the development of energy-efficient, digital, and organizational management solutions [22]-[24]. In this context, increasing attention is being paid to data processing quality, support for innovation, and the introduction of new management approaches that ensure more stable operation of production and technological systems [25], [26].

According to data published in [27], 70-90% of hydraulic system failures are caused by contamination of the working fluid with solid particles, whose concentration and particle-size distribution directly correlate with the wear rate of hydraulic system components. The performance of hydraulic machines depends on the timely detection of faults and the prompt elimination of factors that reduce their operability. The main causes of working fluid degradation include high dust concentrations in the operating environment, exposure to extreme temperatures, and inadequate maintenance. The reliability of hydraulic equipment as a whole is affected by climatic, hydraulic, and mechanical factors [28]. Among these, temperature is particularly important, as it accelerates the degradation of elastomeric and polymer seals, reduces the viscosity of the working fluid, and increases leakage through operating clearances [29]-[31].

The reliability of hydraulic systems in open-pit excavators is critical for the productivity of mining equipment. In 60-70% of cases, the main cause of failure in such systems is contamination of the working fluid and deterioration of its operational properties [32]. Contamination accelerates the wear of pumps, valves, and cylinders, reduces the efficiency of energy transmission, and shortens the service life of hydraulic systems. International studies also emphasize the role of operating factors, such as extreme temperatures, high dust levels, and vibration, which impair oil's viscosity and lubricating properties, thereby further increasing the risk of failure [33]. The additional effect of vibration loads on the durability and operational stability of critical machine components has also been confirmed in studies on damping materials and coatings [34]-[36]. The reliability of hydraulic systems is addressed in the international scientific literature from various perspectives; however, approaches to working fluid quality control and predictive maintenance differ considerably.

To analyze the reliability of hydraulic systems, researchers use a combination of experimental, statistical, and modeling methods. Chinese authors have tested hydraulic cylinders and assessed their durability using the Weibull function and failure distribution analysis [37]. European researchers have tested pumps and valves under the influence of contaminants of different types and particle sizes, recording their effects on dynamic characteristics and component wear [33]. Standardized methods have been applied to assess oil cleanliness, and filtration efficiency has been compared under different operating conditions [38]. Several studies use data from industrial tests and condition monitoring of hydraulic systems in open-pit mining equipment operating under high dust levels and variable temperature conditions [30], [37].

The literature analysis showed that contamination of the working fluid by solid particles, water, and gases is a dominant factor contributing to failures. The authors noted that particles comparable in size to operating clearances can reduce component service life by 30-50% [33]. It has also been shown that the probability of hydraulic cylinder failure varies with load and cycle frequency, enabling the prediction of these units' service life [38]. Studie [39] confirms that high dust levels and extreme temperatures accelerate seal degradation and alter oil viscosity, thereby promoting leakage and reducing hydraulic system efficiency.

A comparison of studies by different authors indicates that the key to improving the reliability of hydraulic systems lies in an integrated approach: monitoring the cleanliness of

the working fluid, selecting filters of the appropriate class, controlling temperature and pressure, and carrying out regular predictive maintenance [40], [41]. Chinese studies demonstrate the effectiveness of failure modeling and prediction, European studies provide practical assessments of the influence of contaminants on the dynamic behavior of hydraulic systems, and the last studies take into account the specific features of operation under severe open-pit mining conditions. The common conclusion is that standardized fluid quality control and the adaptation of maintenance methods to actual operating conditions are necessary to extend the service life of hydraulic systems.

At the same time, existing methodological approaches do not fully reveal the potential for optimizing the operation of hydraulic systems in mining equipment. The mining industrial environment is characterized by a combination of dust, abrasion, chemical activity, and technogenic impacts that can alter the condition of the working media and accelerate the degradation of materials in critical components of equipment. In this regard, dispersed mineral impurities, wear products, and secondary contaminating components formed as a result of industrial processes and the interaction of materials with aggressive media play a significant role [42]-[45]. Increased attention to the reliability and operability of hydraulic systems in mining machines, especially excavators, is therefore clearly necessary. In this context, the development of scientifically grounded methods and technical solutions to improve the efficiency of hydraulic systems has considerable scientific and practical value for the mining and metallurgical industry.

2. Analytical background of failures in hydraulic

Several key advantages of hydraulic excavators over mechanical excavators include greater flexibility in performing work, a smaller power unit and a simpler kinematic scheme. In particular, a hydraulic motor is considerably more compact than an electric motor of comparable power, allowing a more rational machine layout and expanding its operational capabilities [46]. Additional advantages include smoother working movements and reduced vibration levels, which positively affect both equipment durability and operator workplace ergonomics.

Comparative studies show that hydraulic excavators can provide higher productivity under similar mining and technical conditions. For example, during operation at the Krasnobrodsky open-pit mine, the R-9350 hydraulic excavator demonstrated an average hourly productivity 28% higher than that of the EKG-15 mechanical excavator operating under comparable conditions.

A significant share of foreign-manufactured machines characterizes the modern market for open-pit excavators. According to available data, domestically produced open-pit excavators account for approximately 30%, while the main share of equipment is supplied by manufacturers such as Caterpillar, Liebherr, Komatsu, and Hitachi. Over the past 15 years, the gap in supply volumes between electric and hydraulic open-pit excavators has narrowed considerably, and their ratio has approached parity [39], [41], [47].

Practical observations carried out at the Auminzo-Amantaytau open-pit mine indicate that Hitachi machines dominate the hydraulic excavator fleet, accounting for approximately 62% of the total. This includes 35% represented by EX1200-6 models and 27% by EX1200-7 models. More

powerful Hitachi EX3600-6 excavators account for approximately 19%, while Liebherr excavators occupy a comparable share, also close to 19% [48].

Thus, hydraulic excavators combine high productivity, technological flexibility, and relatively simple maintenance, which explains their widespread and priority use in modern open-pit mining practice.

Table 1 presents the average distribution of failures among the main components of single-bucket open-pit hydraulic excavators, with further detail for individual elements [48].

Table 1. Average distribution of failures among the main components of the PC3000 hydraulic excavator

Main component	Elements	Failure rate, %
Working equipment	Bucket, boom, stick, crowd mechanism	25
Undercarriage	Undercarriage components: crawler frame, idlers, crawler chain	10
Electrohydraulic equipment	Components of low-voltage and medium-voltage equipment. Hydraulic system elements: pipeline connections, valves, cylinders	45
Other	Operator cab heating system, ventilation, joysticks	20

Analysis of the presented data shows that the largest share of failures is associated with electrohydraulic equipment, accounting for 45% of all failures. Within this group, hydraulic system components, including pipeline connections, valves, and cylinders, as well as elements of low-voltage and medium-voltage equipment, are of particular importance. Failures of working equipment account for 25%, while undercarriage failures represent 10%. The remaining 20% are related to failures of auxiliary systems, including operator cab heating, ventilation, and control elements. Taken together, these data indicate the decisive role of hydraulic and related systems in the overall failure structure of open-pit excavators.

Table 2 presents the reliability indicators of the PC3000 excavator after 60,700 operating hours, including the total downtime due to failures (STF), mean time between failures (MTBF), and mean time to repair after failure (MTTR) [46]-[49].

Table 2. Reliability characteristics of the PC3000 excavator

Main component	STF, h	MTBF, h	MTTR, h
Working equipment (WE)	1883.5	831.5	25.80
Undercarriage (UC)	1136.0	2168.0	51.64
Electrohydraulic equipment (EHE)	2321.0	3321.14	57.45
Other (O)	1573.0	1011.7	26.21

The values presented allow assessing both the frequency of failures and their consequences, including the duration of repair and restoration activities. The highest total downtime is observed for electrohydraulic equipment, totaling 2321 h, further confirming its critical role in ensuring the machine's operational reliability. This group also exhibits the highest mean time to repair after failure, 57.45 h, indicating the high complexity of repair operations and the significant impact of such failures on the excavator's technical availability.

Hydraulic excavator downtime can be divided into scheduled and unscheduled downtime. Scheduled downtime is associated with regulated activities, including maintenance, preventive repairs, refueling, and the coordination of production operations. Unscheduled downtime occurs unexpectedly and is caused by either technical or organizational factors. Technical factors include various types of malfunctions that require repair, whereas organizational downtime may result from loading delays, poor condition of haul roads, and other external operating conditions.

Analytical data indicate that the predominant share of downtime is associated with failures of mechanical and hydraulic systems, which in most cases are caused by contamination and overheating of the working fluid. Therefore, the uninterrupted and efficient operation of an open-pit excavator is largely determined not only by the overall technical condition of the machine but also by the level of organization of the operating process, including timely monitoring of the hydraulic system condition and the quality of the working fluid.

Figure 1 shows the distribution of the main causes of hydraulic excavator downtime. Analysis of this structure indicates that the hydraulic system is a key contributor to excavator downtime. The largest share of failures is due to working fluid leakage, which is most often caused by wear of hydraulic cylinders, high-pressure hoses, hydraulic motors, and sealing elements. A significant contribution to the overall failure structure also comes from ruptures of pipelines and pressure hoses, as well as failures of connections at fitting attachment points. Taken together, this indicates the dominant role of mechanical wear and loss of tightness in the development of hydraulic system failures in open-pit excavators.

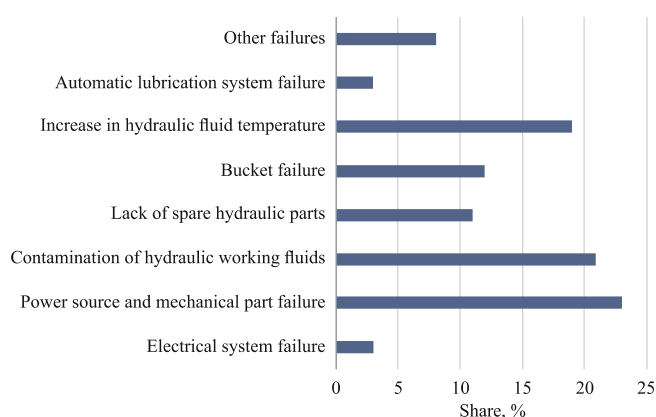


Figure 1. Causes of hydraulic excavator shutdowns

Figure 2 presents the structure of faults occurring in the hydraulic system of open-pit hydraulic excavators.

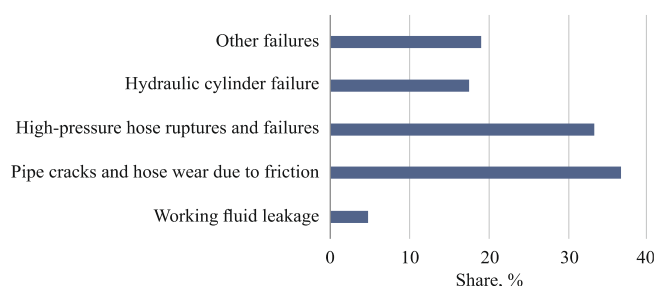


Figure 2. Failure pattern of the hydraulic system in open-pit hydraulic excavators

A generalization of the data presented shows that the technical condition and operating mode of the hydraulic system largely determine the operational performance of machines working under complex mining and geological conditions. The systematic failure of its components results in reduced equipment reliability, longer downtime, and higher operating costs. Therefore, eliminating the main sources of hydraulic system failures and implementing preventive measures to prevent them are important prerequisites for improving the overall technical efficiency of open-pit hydraulic excavators and reducing their specific operating costs.

One of the leading factors contributing to the degradation of hydraulic system performance in mining equipment is the deterioration of working fluid quality. The loss of functional properties of the working medium is caused by operation under conditions of intensive dust generation, exposure to extremely low and high ambient temperatures, and non-compliance with maintenance regulations. Together, these factors impair the lubricating and protective properties of the working fluid, thereby negatively affecting hydraulic system reliability.

Comprehensive studies show that abrasive wear and working fluid contamination are among the key causes of reduced reliability in the hydraulic systems of open-pit excavators [50]. It has been established that the failure resistance of hydraulic system components is primarily affected by the presence of solid particles, high dust levels in the open pit working area, and thermal loads. Standard sealing elements are subject to accelerated wear, whereas structurally improved and imported analogs exhibit higher wear resistance [51].

Dust-laden air containing particles of quartz, silicon dioxide, iron oxide, and other abrasive components intensifies tribological interaction in friction pairs, contributes to working fluid contamination, increases the risk of hydraulic line blockage, and initiates corrosion damage on metal surfaces [52]. In this context, the physical nature of quartz-bearing particles, as one of the most common abrasive components of mining dust, is also of considerable importance [53]. As a result, the wear intensity of hydraulic system components increases, and the overall reliability of the equipment decreases. The mineralogical and physicochemical composition of solid particles formed in the mining environment is also of substantial importance [54]. The mineralogical composition of solid-phase impurities in mining industrial systems may include silicon-bearing components that can intensify abrasive wear on equipment components [55].

Analysis of published data also indicates that the predominant cause of hydraulic system failures in mining machines is working fluid contamination, aeration, and thermal loading [56], [57]. Failure diagnostics enabled identification of the most common mechanisms responsible for the loss of operability of individual components, including failures of axial-piston pumps and hydraulic motors, deformation of spherical surfaces and rods, and wear of piston bores.

The most vulnerable wear zones in hydraulic cylinders include the inner and end surfaces of the cylindrical housing, end caps, seating surfaces of guide seals, outer surfaces of plungers and pistons, and their connection zones. Damage to these areas leads to a loss of tightness, deterioration of hydraulic cylinder performance, and accelerated failure of the hydraulic system as a whole.

Practical experience in hydraulic systems indicates that approximately 30% of failures are associated with regulators, control valves, and actuating devices.

Monitoring of hydraulic-drive operation in open-pit mining equipment showed that failures caused by working-fluid contamination accounted for 69% of total malfunctions. Within this structure, 59% are related to abrasive and erosive wear, as well as shrinkage phenomena caused by the action of solid particles; 14% are associated with clogging of channels and working elements; and 8.2% are attributed to adhesive wear related to the presence of water in the working fluid. These data confirm that contamination of the working medium is one of the determining factors reducing the reliability of hydraulic drives in open-pit mining equipment.

The standard contamination level for the working fluid in hydraulic systems of open-pit mining equipment is class 14-15, whereas class 16-17 is considered acceptable for underground mining equipment. The failure structure of hydraulic systems across different machines, depending on the degree of contamination of the working fluid, is shown in Figure 3.

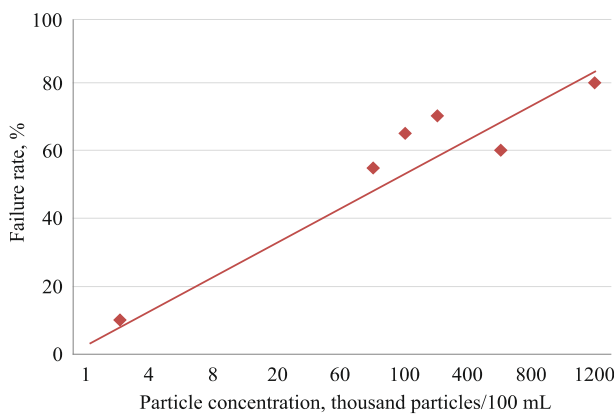


Figure 3. Proportional distribution of hydraulic drive failures associated with working fluid cleanliness

A noticeable decrease in the failure rate of hydraulic machines with precision friction pairs accompanies the shift in failure structure. This has a positive effect on the overall reliability indicators, particularly on the technical availability coefficient, since this category of failures usually causes the greatest time losses due to repair and related equipment downtime.

Figure 4 shows the relationship between the technical availability coefficient of a hydraulic excavator and the ISO 4406 cleanliness class of the working fluid, based on monitored operations over 5872 operating hours. Analysis of this relationship shows that the cleanliness level of the working fluid directly affects the machine's operating performance, including reliability, maintenance-free operation duration, and associated operating costs.

Determining the optimal cleanliness level of the working fluid to minimize operating costs is of universal importance. It can be applied to different types of mining equipment, not just to specific models of open-pit excavators. The obtained results show that cleanliness class 15/13 is economically justified. At the same time, manufacturers of open-pit excavators with a bucket capacity of 15-20 m³ generally recommend maintaining cleanliness classes of 17/15 or 18/16. The tightening of requirements for working fluid cleanliness under modern conditions is associated with the development of filtration technologies and the reduced cost of high-efficiency filter elements.

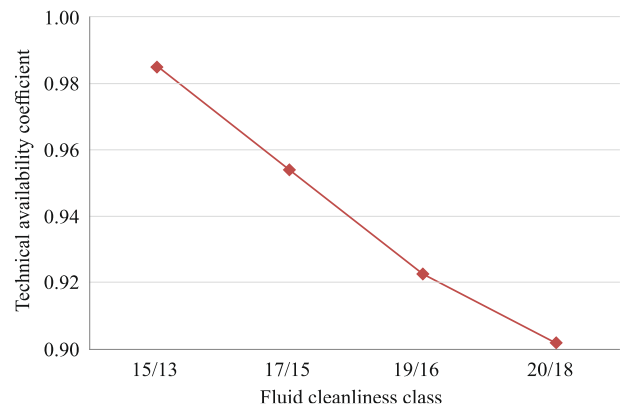


Figure 4. Dependence of the technical availability coefficient of a hydraulic excavator on the ISO 4406 working fluid cleanliness class

The conducted studies, which included diagnostics of hydraulic systems and analysis of working fluids under real operating conditions, enabled quantification of the effect of solid contaminant particles on the reliability and durability of hydraulic components. On this basis, permissible levels of contamination and abrasiveness were determined, and indicative parameters for working-fluid cleanliness were established to ensure more stable, reliable operation of open-pit mining equipment.

The identified analytical relationships highlighted the need for an experimental investigation of the degree of working-fluid contamination and its physicochemical state under real operating conditions.

3. Materials and methods

3.1. Reliability assessment framework

The main reliability indicators considered in relation to the industrial cleanliness level of working fluids include durability and mean time between failures. Durability primarily characterizes the service life of individual units, whereas mean time between failures assesses the service life of systems and machines as a whole.

To quantitatively describe the effect of contamination on the condition of a unit, a family of functions of the following form was used:

$$P_a = k_{cs} \cdot f(C_j), \mu\text{m}, \quad (1)$$

where:

- P_a – critical output characteristic of the unit;
- k_{cs} – coefficient reflecting the sensitivity of the unit to contamination;
- $f(C_j)$ – algebraic function of the concentration of contaminants in the j -th size group.

The target task is to determine the time at which the critical output characteristic reaches its minimum allowable value (P_{aCR}), which corresponds to the failure-free operating interval or the service life of the unit:

$$T_{af} = T(P_{aCR}), \text{h} \cdot \mu\text{m}. \quad (2)$$

In some cases, a parameter that is not directly related to the unit's functional properties is used as the critical characteristic. One example is the absolute wear of components, which can be considered an indicator of structural changes caused by contamination. The unit's structural

analysis justifies this approach. However, it has certain limitations for the design and operation of hydraulic drives, since it does not allow the direct assessment of contamination's effect on system reliability or the economic justification of filtration costs.

3.2. Determination of fluid cleanliness using the Luvatech S41 analyzer

Unscheduled downtime of hydraulic systems largely depends on the cleanliness level of the working fluids. In contrast, one of the main factors causing intensive wear of hydraulic components is the quantity and particle-size distribution of solid particles present in the fluid. For this reason, the present study included an experimental determination of the cleanliness class of hydraulic fluids using the portable laboratory device Luvatech S41.

The Luvatech S41 uses laser particle counting technology and is intended to determine fluid cleanliness class in accordance with ISO 4406, NAS 1638, and GOST 17216. Its operating principle is based on the light-blocking effect: a light beam is directed at a particle suspended in the fluid flow, and the particle size and count are determined from the reduction in laser beam intensity as a function of particle size (Fig. 5).

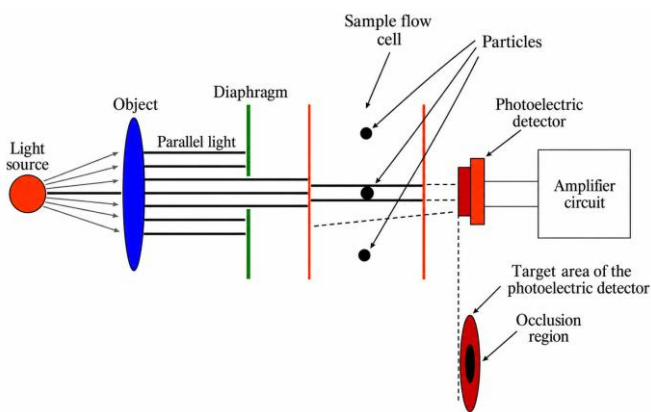


Figure 5. Schematic diagram of the operating principle of the Luvatech S41 device

The experimental study was conducted on working-fluid samples obtained from hydraulic excavators operating under actual production conditions. Samples were collected at intervals of 500 operating hours. Each sample was placed in a sealed container and delivered to the laboratory under conditions ensuring protection from external influences (Fig. 6).

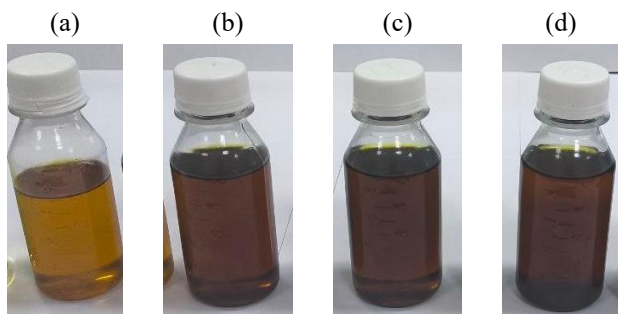


Figure 6. Working fluid samples obtained at different operating times: (a) sample 1, 500 operating hours; (b) sample 2, 1000 operating hours; (c) sample 3, 1500 operating hours; (d) sample 4, 2000 operating hours

Before the measurements, a 100 mL subsample was taken from each fluid sample. Analysis using the Luvatech S41 was performed within a particle size range of 1-100 μm. Each measurement was repeated three times, and the arithmetic mean was used as the final value. The particles were grouped into the following size fractions: 1-2, 2-5, 5-10, 10-25, 25-50, and 50-100 μm. This approach to analyzing particle-size composition is consistent with the general objective of determining the size distribution of solid impurities in the studied media [58].



Figure 7. Parameter selection windows for measurements using the portable laboratory device Luvatech S41

Thus, the use of the Luvatech S41 enabled the implementation of a standardized procedure for determining the cleanliness class of working fluids, accounting for both the number and size distribution of solid particles. The adopted sampling procedure, storage conditions, and repeated measurements ensured the comparability of the obtained data. It provided a basis for further analysis of changes in working-fluid contamination over the course of equipment operation.

3.3. Model for estimating the effect of contamination on hydraulic unit life

To assess the effect of working fluid cleanliness on the service life of hydraulic system components, the relationship proposed by B.V. Slesarev was used. This relationship was developed to analyze the influence of contaminants on the service life of units in open-pit hydraulic excavators:

$$R_c = R_{c(ecs)} \cdot \left[\left(\frac{P_{c(ecs)}}{P_c} \right)^a \left(\frac{v_{c(ecs)}}{v_c} \right) \right] \cdot \left[\left(\frac{d_{c\sum(ecs)}^{2.77}}{d_c^{2.77}} \right) \left(\frac{C_{ecs}}{C_c} \right) \right], \quad (3)$$

where:

- R_c – theoretical operating life, operating hours;
- $R_{c(ecs)}$ – theoretically specified service life, operating hours;
- $P_{c(ecs)}$ – theoretically specified pressure, Pa;
- P_c – pressure in the hydraulic system, Pa;
- a – pressure difference coefficient ($a = 1$);
- $v_{c(ecs)}$ – theoretically specified velocity of working fluid, m/s;
- v_c – velocity of the working fluid in hydraulic system, m/s;
- $d_{c\sum(ecs)}^{2.77}$ – theoretical particle size in the working fluid, mm;
- $d_c^{2.77}$ – particle size in the working fluid of the hydraulic system, mm;
- C_{ecs} – theoretical concentration of contaminant particles, kg/kg;

C_c – concentration of contaminant particles in the hydraulic system, kg/kg.

At the same time, determining the actual concentration of contaminants C_c during hydraulic system operation is associated with considerable practical difficulty. In calculation procedures, this parameter is often assumed to equal the average of the specified range, which reduces the accuracy of the results. To improve the accuracy of assessing the effect of contamination on unit life, the parameter C_c was refined as follows:

$$R_c = R_{c(ec)} \cdot [k_r \cdot k_v] \cdot \frac{d_{c\sum(ec)}^{2.77}}{d_c^{2.77}} \cdot \frac{3\pi \cdot 10^{-6} \left(\frac{\rho_{ch}}{\rho_m} \right) \cdot d_i^3 \cdot n_{ch(ec)}}{3\pi \cdot 10^{-6} \left(\frac{\rho_{ch}}{\rho_m} \right) \cdot d_c^3 \cdot n_{ch_{1-2}} \cdot n_{ch_{2-5}} \cdot n_{ch_{5-10}} \cdot n_{ch_{10-25}} \cdot n_{ch_{25-50}} \cdot n_{ch_{50-100}}}, \quad (5)$$

where:

- $n_{ch(ec)}$ – reference number of contaminant particles;
- k_r – pressure coefficient;
- k_v – velocity coefficient.

Thus, the proposed model allows consideration not only of generalized contamination parameters but also of the actual particle size distribution. This improves the accuracy of assessing the influence of working fluid contamination on the service life of hydraulic units.

$$S_i = \delta \cdot n_{ch(i)} = 3\pi \cdot 10^{-6} \left(\frac{\rho_{ch}}{\rho_m} \right) \cdot d_i^3 \cdot n_{ch(i)}, \quad (4)$$

where:

- ρ_{ch} – particle density, kg/m³;
- ρ_m – density of the working fluid, kg/m³;
- n_{ch} – number of contaminant particles in hydraulic system.

Taking expression (4) into account, the initial relationship (3) was transformed into the following form:

3.4. Working fluids and physicochemical characterization methods

The objects of the study were hydraulic fluids of the Tellus-68, Tellus-46, Chilon-68, Chilon-46 grades, both in their initial state and after operation. Their physical characteristics, including density and kinematic viscosity, are given in Table 3. Structural changes in the samples were evaluated by FTIR spectroscopy. The spectra were recorded using an IR Tracer-100 spectrometer (Shimadzu) in the wavenumber range of 4000-400 cm⁻¹.

Table 3. Physical characteristics of the working fluids under study

No.	Hydraulic fluid grade	Solvents					Density, (ρ), g/cm ³	Time, (t), s	Viscosity, (η), Pa·s
		Water	Butanol	Cyclohexane	o-Xylene	Gasoline			
1	Chilon-46	I	SS	SS	I	S	0.869	15.5	13.46
2	Chilon-68	I	SS	SS	I	I	0.874	16.2	14.16
3	Chilon-68 (haul)	I	SS	SS	I	S	0.827	12.5	10.34
4	Tellus-46	I	SS	SS	I	S	0.863	13.1	11.31
5	Tellus-68	I	SS	SS	I	SS	0.865	18.0	15.57
6	Tellus-46	I	SS	SS	I	S	0.752	5.6	4.21
7	Initial working fluid	I	SS	SS	I	S	0.880	20.5	18.04

Note: I – insoluble; SS – slightly soluble; S – soluble

In addition, the condition of the oils was assessed visually by observing color changes during operation. To select potentially effective purification methods, an experimental evaluation of several organic solvents was conducted to assess their ability to remove contaminating impurities.

Semi-quantitative X-ray fluorescence analysis of hydraulic fluids used in mining and metallurgical equipment was performed using a Shimadzu EDX-7000 spectrometer (Japan). Sample preparation included calcination of 100 g of soil in a CNOL-24/200 laboratory drying oven at 800°C for 1 hour, followed by grinding to a particle size of 0.074 μm, addition of 100 g of used oil, and thorough homogenization of the mixture. The prepared sample was then subjected to spectral analysis.

To improve the accuracy and reproducibility of the spectral data, the analytical protocol was refined. A local soil sample, specifically sand, previously characterized under laboratory conditions, was used as a matrix standard for calibration and comparative measurements. This approach provided initial elemental composition data required for the subsequent correct interpretation of the results obtained for the hydraulic fluids. Thus, the combined application of FTIR spectroscopy, visual assessment, and X-ray fluorescence analysis provided a comprehensive methodological basis for studying the physicochemical conditions of working fluids and for identifying contaminant impurities of different origins.

4. Results and discussion

4.1. Particle-size distribution and evolution of contamination during operation

Analysis of the obtained data showed that the number of particles in the working fluid generally increases with increasing operating time of the equipment. However, the pattern of change depends on the particle-size fraction. The most pronounced upward trend was observed for particles sized 2-5 and 5-10 μm, which indicates intensification of abrasive wear processes in the hydraulic system (Fig. 8).

For the 1-2 μm fraction, a gradual increase in particle number was observed over the 500-1000 operating hour interval, followed by a short-term decrease at 1500 operating hours. This decrease may be due to effective retention of fine-dispersed impurities by the filtration system or to a temporary change in operating conditions. By 2000 operating hours, the number of particles in this fraction increased again, indicating deterioration in working fluid cleanliness and the progression of wear in hydraulic components (Fig. 8a).

The behavior of particles sized 2-5 μm is characterized by a substantial increase already within the 500-1000 operating hour interval, reflecting the activation of the initial stages of abrasive wear. The relative decrease at 1500 operating hours is temporary in nature and does not alter the overall trend.

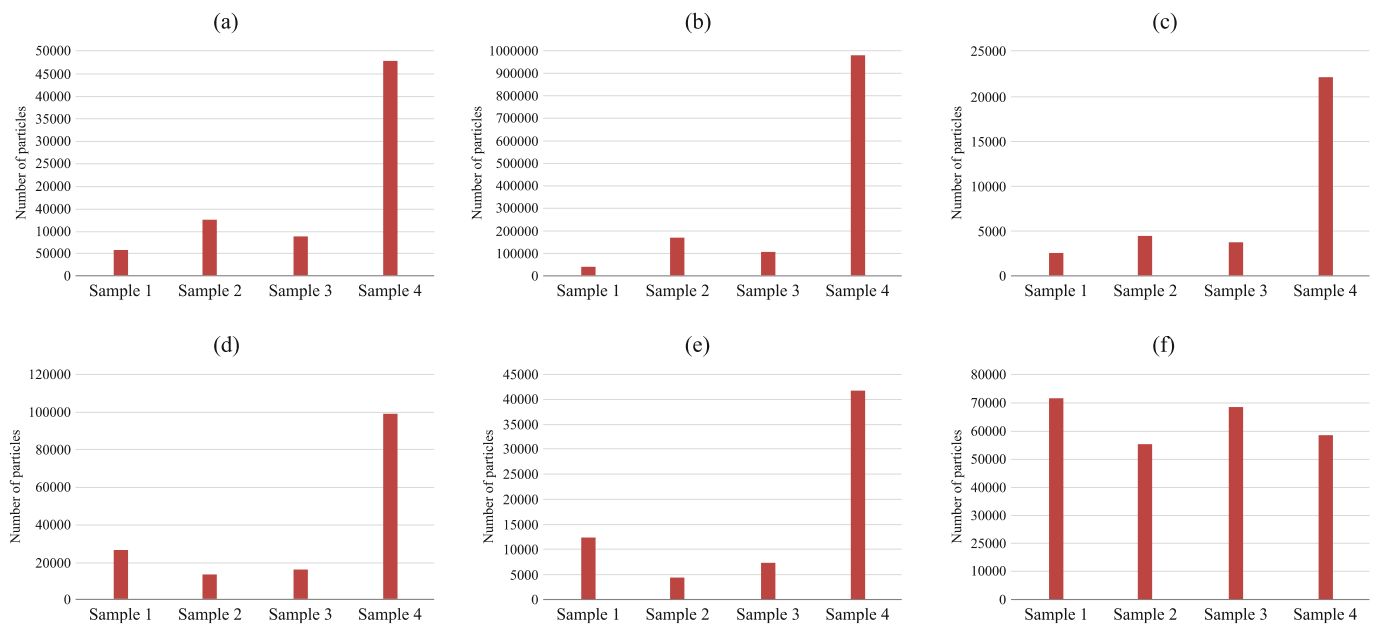


Figure 8. Changes in the number of contaminant particles in different size fractions in working fluid samples at different operating times: (a) 1-2 μm ; (b) 2-5 μm ; (c) 5-10 μm ; (d) 10-25 μm ; (e) 25-50 μm ; (f) 50-100 μm

The sharp increase in particle count at 2000 operating hours indicates that contamination of the working fluid has reached a critical level and that degradation processes in the hydraulic system are progressing rapidly (Fig. 8b).

A similar pattern was established for the 5-10 μm fraction. The increase in particle count over the 500-1000 operating hours indicates the development of abrasive wear in the hydraulic system. The slight decrease in concentration at 1500 operating hours may be due to temporary stabilization of operating conditions or improved filtration efficiency. At the same time, the sharp rise in particle number at 2000 operating hours confirms a high degree of working fluid contamination and intensified degradation of hydraulic components (Fig. 8c).

The change in concentration of particles sized 10-25 μm is characterized by a relatively high initial value at 500 operating hours, followed by a decrease in the 1000-1500 operating-hour interval. This may be explained by effective filtration or temporary normalization of the operating regime. A sharp increase in particle count at 2000 operating hours indicates the formation of larger abrasive particles in the hydraulic system and an intensification of surface-damage processes, confirming accelerated component degradation and reduced system reliability (Fig. 8d).

For the 25-50 μm fraction, a comparatively high initial particle content was also observed at 500 operating hours. The decrease in concentration at 1000 operating hours may be due to the filtration system's effective operation or to a temporary improvement in operating conditions. A repeated increase in particle number at 1500 operating hours indicates the onset of large-wear product formation, while the sharp peak at 2000 operating hours points to intensive wear of hydraulic components and the transition of the system to a critical stage of degradation (Fig. 8e).

The behavior of the largest particles (50-100 μm) differs: a high initial value was recorded at 500 operating hours, followed by a decrease at 1000 operating hours, most likely due to the filtration system's effective removal of the coarse fractions. The subsequent increase in particle content at 1500 operating hours indicates the formation of secondary wear

products. The relative stabilization of this indicator at 2000 operating hours does not imply the cessation of degradation processes, but rather indicates the persistent presence of large particles in the system (Fig. 8f).

Overall, the obtained relationships show that increasing operating time not only increases the overall contamination level of the working fluid but also alters its fractional composition. The most diagnostically significant fractions are 2-5 and 5-10 μm , which most clearly reflect the development of abrasive wear. They may therefore be considered indicators of deterioration in the hydraulic system's technical condition (Fig. 8b,c).

4.2. Particle-size distribution and evolution of contamination during operation

The results of studying the effect of working fluid condition on the reliability and service life of hydraulic system components confirmed that units and elements of hydraulic systems in open-pit mining equipment operating with contaminated working fluids are less reliable and are more prone to failure. Based on the obtained results, graphical relationships were derived showing the dependence of hydraulic system component life on contamination level (Fig. 9).

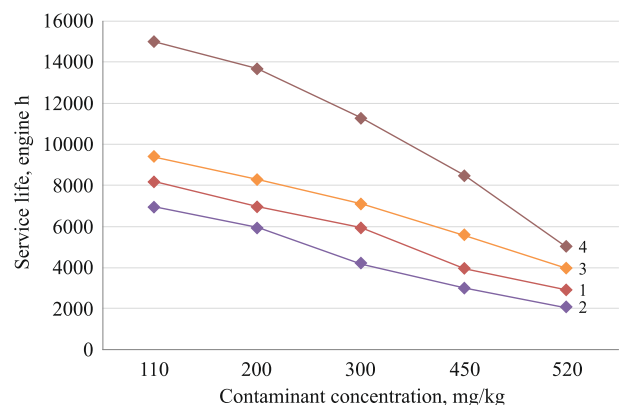


Figure 9. Effect of working fluid contamination on the service life of hydraulic units: 1 – axial piston pump; 2 – hydraulic control valve; 3 – hydraulic cylinder; 4 – hydraulic motor

The service life of the main components of hydraulic systems in mining machines depends on several factors, among which contamination of the working fluid and abrasiveness have the greatest adverse effect. Graphical relationships describing the dependence of excavator hydraulic unit life on the cleanliness class of the working fluid are presented.

The studies conducted enabled the determination of permissible levels of contamination and abrasiveness, as well as the optimal cleanliness level of hydraulic fluid for hydraulically operated mining machines (Fig. 10).

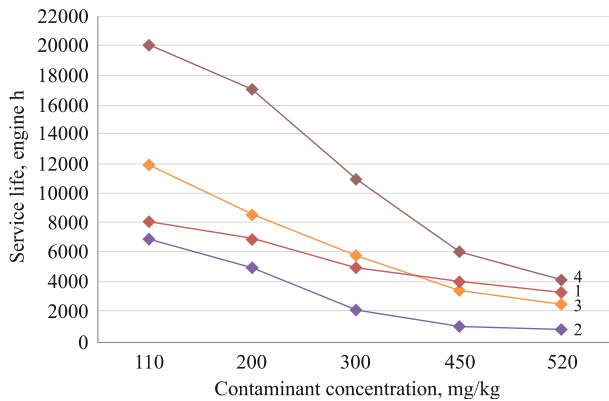


Figure 10. Service life of excavator hydraulic units depending on the cleanliness class of the working fluid: 1 – axial piston pump; 2 – hydraulic control valve; 3 – hydraulic cylinder; 4 – hydraulic motor

Studying the relationship between working-fluid cleanliness and the performance of hydraulic units enabled a quantitative assessment of hydraulic component reliability. For open-pit excavators, maximum permissible levels of working fluid contamination by particles and component wear were established, and the optimal cleanliness level required for efficient use was determined.

Experiments with the Luvatech S41 device showed that the particle count in the hydraulic working fluid is nonuniform and increases with machine operating time. Samples were taken after 500, 1000, 1500, and 2000 operating hours. A sharp increase in particle numbers was observed in the 2-5, 5-10, and 10-25 μm size ranges. This increase indicates the gradual intensification of abrasive wear in friction pairs, seals, hydraulic cylinders, control valves, and pumps of the hydraulic system. As a result, abrasive wear becomes more pronounced, significantly affecting the system's condition.

Comparison of the experimental results with the graphical relationship shown in Figure 9 demonstrates a decrease in service life with increasing contamination, expressed in mg/kg. The experiment confirms that the particle content in the initial samples corresponding to 500 operating hours is relatively low, ranging from 110 to 200 mg/kg. In this range, hydraulic components operate stably, the oil film remains sufficient, and wear develops slowly. In the 1000-1500 operating hours interval, particle content increases sharply to 200-300 mg/kg, and in some cases to 300-450 mg/kg. With such an increase in particle content, the hydraulic system's efficiency decreases. At this stage, abrasive particles actively penetrate the friction zones, microspalling intensifies, and service life depletion accelerates. The sample corresponding to 2000 operating hours shows a very high level of contamination, which corresponds to the critical range of 450-520 mg/kg in the graph. Under these conditions, all

hydraulic components are subject to rapid wear, and failures occur more frequently in the system.

A similar tendency is confirmed by the reduction in service life with increasing ISO 4406 cleanliness class when the Luvatech S41 results are compared with Figure 10. According to the experimental data, contamination in the initial samples remains at a relatively controlled level, approximately corresponding to ISO class 15. The increase in particle count in subsequent samples, especially after 1500 and 2000 operating hours, indicates a deterioration in cleanliness class to the range 16-18. As shown in the graph, once ISO class 14 is exceeded, the service life of hydraulic units decreases not linearly, but at a markedly higher rate. Therefore, the increase in particle count detected by the Luvatech S41 reduces the operating life of hydraulic units due to deterioration in working fluid cleanliness.

It should be noted that most of the fractions detected by the Luvatech S41 consist of particles in the 2-5 and 5-10 μm size ranges. These fine particles can penetrate the working clearances between hydraulic friction pairs, where they interact with contacting surfaces and disrupt the viscous oil film, becoming the main source of micro-abrasive wear. The filter can often retain larger particles, whereas finer particles circulate more freely throughout the system and therefore cause the greatest damage to sensitive components such as pumps, hydraulic control valves, and hydraulic motors. For this reason, the significant reduction in the service life of hydraulic cylinders and pumps shown in the graphs is fully consistent with the results obtained using the Luvatech S41.

The experimental results also allow analysis of another important feature: the reduction in service life with increasing contamination does not follow a simple proportional relationship. At the initial stage, the service life decreases slowly. However, when the particle content reaches a critical threshold, wear processes in the hydraulic system accelerate sharply. Therefore, the relationship between contamination and service life in hydraulic systems can be summarized as follows: initially, the oil retains its protective properties; as particle content increases, the protective film is disrupted; finally, the system enters a stage of intensive abrasive wear. These three stages are clearly reflected in the graphical relationships, while the Luvatech S41 results explain their physical origin.

The experimental data obtained using the Luvatech S41 convincingly confirm the identified patterns. During operation, a clear tendency towards an increase in the number of particles in the working fluid is observed. This leads to a deterioration in cleanliness levels and is directly associated with a worsening of the ISO cleanliness class. As a result, the operating life of hydraulic units is significantly reduced. Thus, the Luvatech S41 can be regarded as an important diagnostic tool that enables objective assessment not only of laboratory indicators but also of the actual technical condition of the hydraulic system.

4.3. X-ray fluorescence analysis of hydraulic fluid contamination

The implemented X-ray fluorescence analysis procedure enabled the determination of chemical element concentrations in hydraulic fluids. The results obtained for the matrix standard confirmed the applicability of this method for diagnostic purposes in mining and metallurgical engineering. Using a Shimadzu EDX-7000 spectrometer (Japan), a com-

parative X-ray fluorescence analysis was performed on the initial matrix sample and the matrix sample after the addition of used oils. In both cases, a comparative approach was applied, with the composition of the initial matrix first determined by X-ray fluorescence spectrometry. The resulting spectra are presented in Figure 11. The identified chemical elements and their concentrations in the matrix sample are summarised in Table 4.

Based on the results presented in [39], it can be established that X-ray fluorescence analysis is applicable for monitoring the condition of hydraulic fluids used in mining equipment. The obtained spectra indicate that this method is a suitable tool for assessing the quality of hydraulic fluids in equipment. It not only detects the presence of various chemical elements but also quantitatively determines their concentrations in the fluid.

Comparative analysis of spectra and quantitative data shows that adding used oils to the investigated matrix alters the sample's elemental composition. The most significant change is observed in silicon dioxide, whose concentration

increases from 88.740 to 93.474%. The increase in the SiO₂ content indicates the presence of silicon-bearing abrasive particles in the working fluid and confirms its contamination by mineral impurities.

The obtained results show that X-ray fluorescence analysis is an informative method for monitoring the condition of hydraulic fluids used in mining equipment. This approach enables not only the identification of individual chemical elements but also the quantitative assessment of their content. This, in turn, enables contamination diagnostics, component wear assessment, and early detection of potential hydraulic system failures.

The conducted studies confirmed the possibility of effectively applying X-ray fluorescence analysis for the quantitative determination of SiO₂, Fe, Al, Ti, Mn, Sr, V, Ca, K, Cr, Zn, Cu, Zr, and several other elements in working fluids. This opens up prospects for operational contamination monitoring, assessment of equipment component wear, and early detection of potential failures.

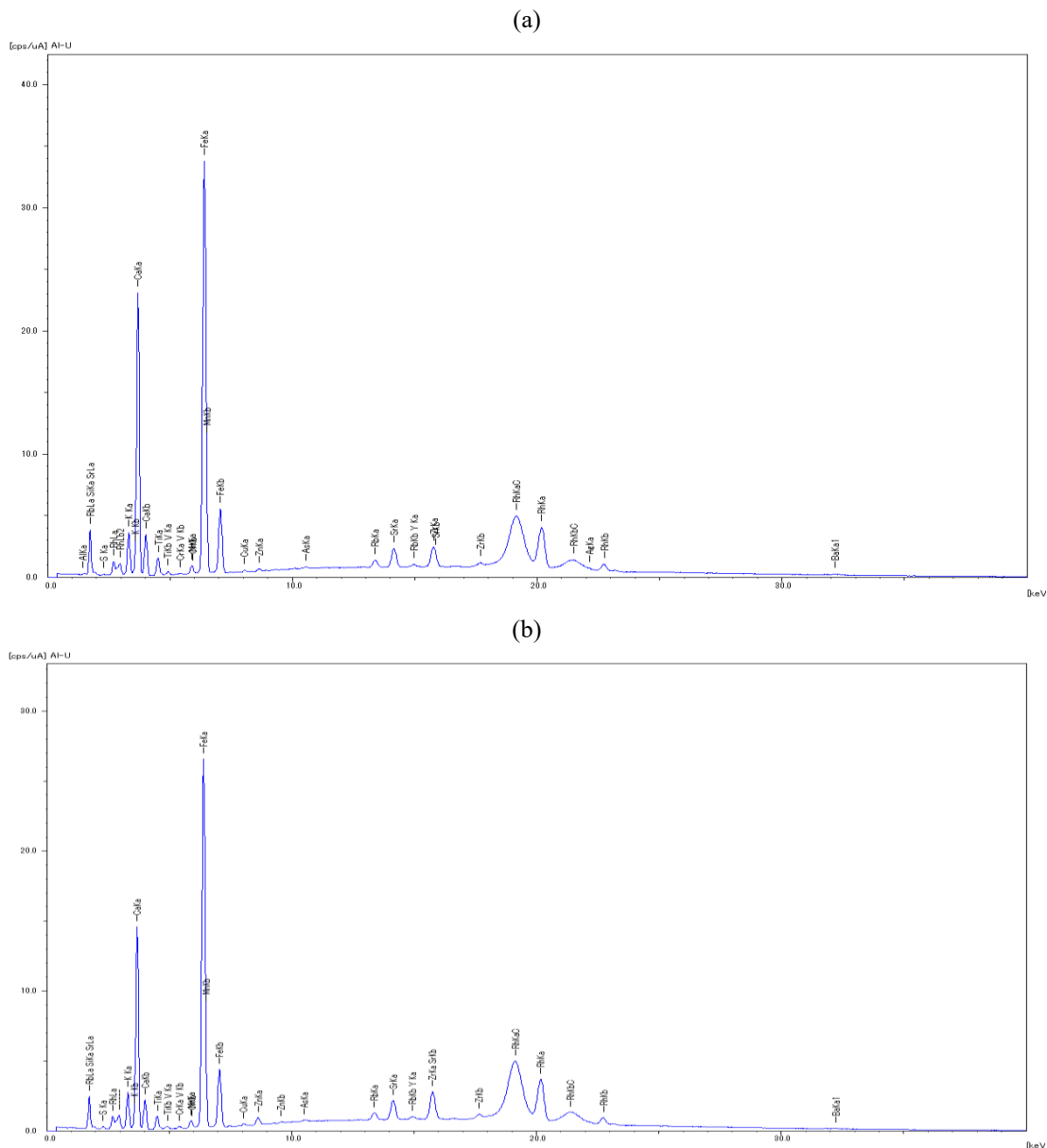


Figure 11. Comparative X-ray fluorescence spectra of the investigated samples: (a) initial matrix sample; (b) matrix sample after the addition of used oils

Table 4. Comparative results of X-ray fluorescence analysis of chemical elements in the matrix sample and in the sample after the addition of used oils

Chemical element	Matrix sample				Matrix sample after the addition of used oils			
	Concentration, %	KHV	Element and emission line	Energy, keV	Concentration, %	KHV	Element and emission line	Energy, keV
Ca	6.231	0.026	CaK α	145.861	3.847	0.019	CaK α	91.398
K	1.601	0.016	KK α	22.156	1.175	0.013	KK α	161.160
Al	1.519	0.275	AlK α	0.465	–	–	–	–
Fe	1.516	0.005	FeK α	258.802	0.090	0.004	FeK α	203.879
Ti	0.217	0.003	TiK α	10.006	0.134	0.002	TiK α	6.686
S	0.062	0.013	SK α	0.339	0.178	0.014	SK α	0.966
Mn	0.037	0.037	MnK α	4.664	–	–	–	–
Sr	0.021	0.000	SrK α	17.348	0.021	0.000	SrK α	17.348
Zr	0.018	0.018	ZrK α	16.772	0.018	0.018	ZrK α	16.772
V	0.009	0.009	VK α	0.581	0.009	0.009	VK α	0.581
Rb	0.008	0.000	RbK α	6.398	0.008	0.000	RbK α	6.398
Cr	0.006	0.001	CrK	0.550	0.006	0.001	CrK	0.550
Ag	0.006	0.001	AgK α	1.930	–	–	–	–
Zn	0.005	0.000	ZnK α	1.781	0.005	0.000	ZnK α	4.614
Cu	0.003	0.000	CuK α	10.308	0.003	0.000	CuK α	1.071
Y	0.001	0.000	YK α	1.216	0.001	0.000	YK α	1.351
SiO ₂	88.740	–	SiOK α	–	93.474	–	SiOK α	–

4.4. Microscopic and infrared spectroscopic characterization of used hydraulic fluids

One of the main causes of hydraulic system failure in mining equipment is the ingress of solid particles into the hydraulic fluid, including metallic inclusions, seal residues, and dust. Figure 12 presents the results of a microscopic examination of Tellus-68 hydraulic fluid after 3560 operating hours, demonstrating the presence of impurities and their effect on system performance.

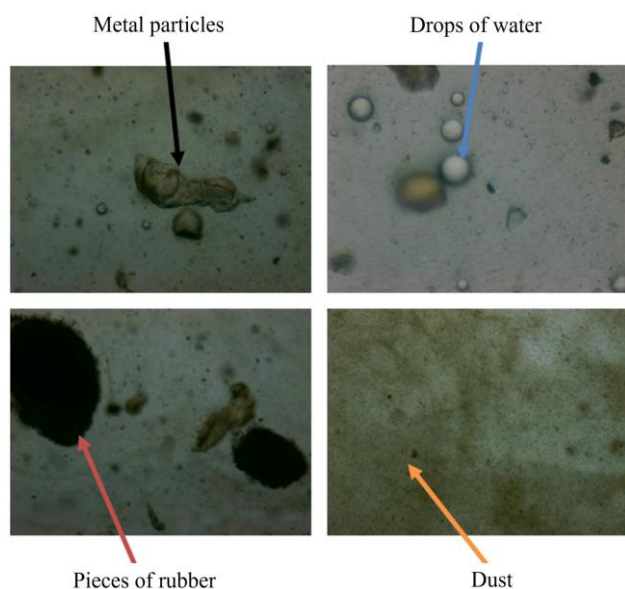


Figure 12. Microscopic analysis of contamination in Tellus-68 working fluid after 3560 operating hours

The ingress of water into hydraulic fluid is a key factor contributing to corrosion and various forms of damage to hydraulic system components. The corrosive effect of the liquid medium on metallic components is also supported by findings from other studies on sulfate-containing systems [59].

The main causes of moisture in hydraulic fluid include steam cleaning of equipment, condensation from contact with atmospheric air, malfunctioning oil coolers (including leaks in

the cooling system), fluid splashing, the use of contaminated fresh oil, and seal leakage. The presence of water in hydraulic fluid not only accelerates corrosion but also impairs the oil's lubricating properties, increases wear on pumps, valves, and other components, and reduces the reliability and service life of the hydraulic system. Monitoring and preventing moisture ingress into hydraulic fluid are therefore essential for maintaining the efficient operation of hydraulic equipment.

The density of the working fluids ranged from 0.827 to 0.880 g/mL, while the viscosity of the used fluids decreased relative to that of the initial fluid. Analysis of the IR spectrum of the initial working fluid reveals characteristic absorption bands. In the region near 2910 cm⁻¹, bands corresponding to the stretching vibrations of C–H bonds are observed. For CH₂ groups and carboxyl fragments (–COOH), more intense bands appear near 2854 cm⁻¹. Low-intensity bands in the 2364–2345 cm⁻¹ range can be attributed to vibrations of the RC≡R1 fragment. In the 1720–1543 cm⁻¹ region, bands characteristic of α - and β -unsaturated ketones are recorded. More pronounced bands at 1462 cm⁻¹ correspond to deformation vibrations of CH₃C or (CH₃)₂C groups, while absorption at 1377 cm⁻¹ is associated with C–O stretching vibrations in ester groups (–COO–) and O–H deformation vibrations (≡C–OH). The band in the region of 725 cm⁻¹ can be attributed to vibrations of the –C=C– fragment [39], [57].

The IR spectral analysis shows that the fundamental absorption bands of the initial fluid are preserved after distillation. At the same time, additional absorption bands with maxima at 964 and 459.4 cm⁻¹ were detected in the used working fluids, reflecting changes in composition under the influence of operating factors (Fig. 13a–c). This indicates changes in chemical composition and the possible occurrence of oxidation and structural transformation of oil components [39], [60].

According to the IR spectra (Table 5), the investigated working fluids can be classified as synthetic organic compounds based on their chemical structures. The composition of the studied fluids includes characteristic functional groups, including carboxylate (–COO–), hydroxyl (–OH), and hydrocarbon chains with multiple bonds (–C=C–, –C≡C–). The corresponding infrared absorption bands confirm the presence of these structural elements.

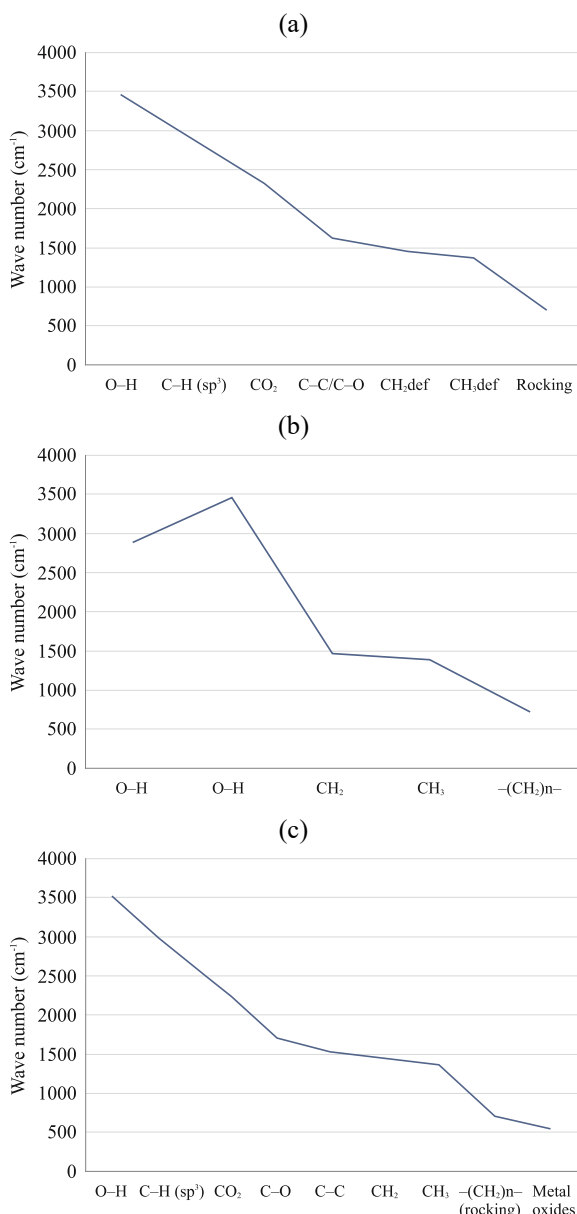


Figure 13. Comparative infrared spectra of working fluid samples: (a) distilled Chilon-68; (b) Chilon-68 residue; (c) initial sample

Table 5. Vibrational frequencies of selected inorganic impurities (cm⁻¹)

Impurity/compound	v1	v2	v3	v4
[SiO ₄] ⁴⁻	800	500	1050	625
[PO ₄] ³⁻	970	358	1080	500
[SO ₄] ²⁻	983	450	1105	611
[Al(OH) ₄] ⁻	615	310	720	310
CaSO ₄	1018	415, 499	415, 1136, 1144	618, 622, 672

Within the framework of this study, a classification of hydraulic fluids was developed, and the main parameters to be determined in their composition were identified. Sampling methods were established, and the applicability of spectral analysis for the quantitative determination of specific indicators was carefully assessed. These steps enabled classification of analytical methods by their suitability for different diagnostic purposes.

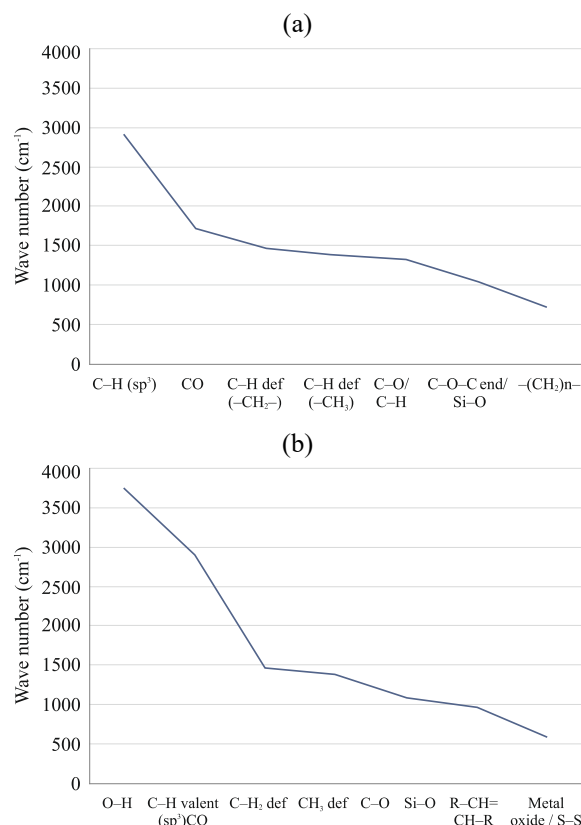


Figure 14. Comparative infrared spectra of working fluid samples: 1 – distilled Tellus-68; 2 – Tellus-68 residue

The study of the negative effect of working fluid contamination on the overall performance of the hydraulic system showed that the effective operation of hydraulic system components largely depends on the condition of the hydraulic working medium.

When exposed to air, the working fluid can become contaminated during transportation in open containers or during filling into the hydraulic tank. Contamination may also occur when dust-laden air enters the hydraulic tank through its breather opening or is drawn in through a poorly sealed connection in the hydraulic system.

The results showed that, among the factors that reduce the reliability of hydraulic systems, the condition of the working medium is of primary importance. The analysis indicates that the problem is not limited to mechanical contamination, since chemical degradation processes also affect system stability. In particular, the presence of siliceous abrasive particles indicates that environmental factors play a decisive role under open-pit mining conditions. This leads to rapid service-life depletion of hydraulic units operating with precision friction pairs.

The results of IR spectroscopic analysis confirmed that structural changes occur in the working fluid, indicating that oxidation processes are activated by high temperature, air contact, and moisture. Therefore, ensuring reliability requires not only improved filtration but also control over the fluid's chemical stability.

It was established that improving the cleanliness class increases the service life of hydraulic units, confirming the economic feasibility of improving filtration systems. At the same time, the integrated application of diagnostic methods enables early assessment of the hydraulic system's condi-

tion, which is important for developing a preventive maintenance strategy. Thus, the study's results indicate the need for comprehensive management of mechanical, chemical, and operational factors to improve the reliability of hydraulic systems. They also demonstrate that an integrated approach to fluid condition monitoring is required: the combined use of spectroscopic, microscopic, and X-ray fluorescence analyses enables the development of a reliable diagnostic system.

5. Conclusions

The conducted studies established that 60-70% of failures in hydraulic systems of open-pit hydraulic excavators are associated with working fluid contamination. Of these failures, 59% are caused by abrasive and erosive wear under the action of solid particles, 14% by clogging of channels and working elements, and 8.2% by adhesive wear due to water saturation. The results showed that improving the working fluid cleanliness class from 17/15-18/16 to 15/13 according to ISO 4406 significantly increases the service life and technical availability coefficient of hydraulic units. X-ray fluorescence analysis showed that the SiO₂ content increased from 88.740 to 93.474%, confirming that the working fluid was mainly contaminated by silicon-bearing abrasive particles. Microscopic analysis of Tellus-68 oil after 3560 operating hours revealed a high concentration of solid particles. At the same time, the appearance of additional bands in the IR spectrum at 964 and 4594 cm⁻¹ confirmed the occurrence of chemical degradation processes in the working fluid. These quantitative results scientifically demonstrate that working fluid cleanliness is a decisive factor in improving the reliability of hydraulic systems.

The results of this study contribute to the further development of the reliability theory of hydraulic systems, provide a scientific basis for establishing the functional relationship between working fluid cleanliness and the service-life parameters of hydraulic units, and support improvements in diagnostic methods. The integrated use of FTIR spectroscopy, X-ray fluorescence analysis, and microscopic examination provides a scientific basis for assessing the condition of hydraulic systems at an early stage and for developing predictive maintenance models. The obtained results also provide a theoretical and practical foundation for further research aimed at improving filtration technologies, increasing the chemical stability of working fluids, and enhancing the energy efficiency of mining equipment.

Author contributions

Conceptualization: NA, LA, RM; Data curation: KN; Formal analysis: JT, AZ; Funding acquisition: RM; Investigation: KN, AZ; Methodology: JT; Project administration: KN, RM; Resources: KN; Software: RM; Supervision: NA; Validation: KN; Visualization: BB; Writing – original draft: NA, JT, LA, KN, AZ; Writing – review & editing: JT, KN, AZ, BB, RM. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Оцінювання факторів, що спричиняють відмови гідравлічних систем кар'єрних екскаваторів

Н. Абдуазізов, Ж. Тошов, Л. Абдієва, Х. Нурбол, А. Жураєв, Б. Баратов, Р. Мухаммедрахим

Мета. Виявлення та кількісне оцінювання основних факторів, що спричиняють відмови гідравлічних систем кар'єрних екскаваторів, з акцентом на вплив чистоти та фізико-хімічного стану робочої рідини на надійність і ресурс гідроагрегатів.

Методика. Дослідження ґрунтується на комплексному підході, що включає аналітичне узагальнення літературних та експлуатаційних даних щодо несправностей гідросистем, визначення класу чистоти робочих рідин із використанням лічильника частинок Luvatech S41, а також фізико-хімічну характеристику рідин методами інфрачервоної спектроскопії, рентгенофлуоресцентного аналізу, візуального оцінювання та мікроскопії. Вплив забруднення на ресурс гідроагрегатів додатково оцінювали за допомогою розрахункової моделі, яка враховує концентрацію та розмірний розподіл частинок.

Результати. Встановлено, що забруднення робочої рідини є причиною приблизно 70% відмов гідравлічних систем. Аналіз кількості частинок показав прогресуюче зростання забрудненості зі збільшенням напруження обладнання, причому найбільш виражене зростання спостерігалось для фракцій 2-5 і 5-10 мкм, що свідчить про інтенсифікацію абразивного зношування в гідросистемі. За результатами рентгенофлуоресцентного аналізу встановлено збільшення вмісту SiO₂ з 88.740 до 93.474%, що вказує на забруднення робочої рідини кремнієвмісними абразивними частинками. Інфрачервона спектроскопія виявила структурні зміни робочої рідини та появу додаткових смуг поглинання, пов'язаних із її хімічною деградацією в процесі експлуатації. Мікроскопічне дослідження відпрацьованої оливи підтвердило наявність твердих домішок. Визначено економічно й технічно обґрунтований рівень чистоти робочої рідини, що відповідає класу ISO 4406 15/13 і забезпечує підвищення надійності та зниження експлуатаційних витрат.

Наукова новизна. Вперше застосовано комплексний підхід, який поєднує аналіз розмірного складу частинок, фізико-хімічну діагностику робочої рідини та оцінювання ресурсу гідроагрегатів для встановлення взаємозв'язку між чистотою робочої рідини, характеристиками забруднення та надійністю гідравлічної системи в реальних умовах експлуатації.

Практична значимість. Отримані результати можуть бути використані для вдосконалення систем фільтрації, оптимізації стратегій технічного обслуговування, а також для ранньої діагностики та впровадження прогнозного обслуговування гідравлічного обладнання на гірничодобувних підприємствах.

Ключові слова: кар'єрний екскаватор; гідравлічна система; робоча рідина; забруднення; відмови; інфрачервона спектроскопія; рентгенофлуоресцентний аналіз

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