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Assessment of mine water solid phase impact on section pumps performance in the development of kimberlite ores

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Abstract

Despite innovations in ALROSA's (PJSC) mining and processing complexes under the updated strategy for economic development, practice shows that in recent few years the operating costs of the section pumps at the Udachny underground mine's main drainage have increased significantly. Such an increase could be the result of a concentration of mechanical impurities in the mine water. This study is aimed at the integrated assessment of the impact of mechanical impurities concentration in mine water on the performance of the Udachny underground mine's main drainage section pumps. It is also aimed at studying the feasibility of sinking additional inclined clarifying working-reservoirs. The target goal was achieved by means of visual, analytical, statistical, and other types of research in determining the impact of the concentration of mechanical impurities in mine water on the performance indicators of section pumps of the kimberlite mine's underground drainage facilities. The integrated studies showed that the concentration of mechanical impurities in mine water is the key factor in determining the overhaul life and electricity demand of pumping equipment. The Udachny underground mine's main drainage section pumps overhaul life can be calculated as a linear function of their delivery rates at the moment of taking-down for overhaul. This function is reliably described by empirical expression $Q = -7.5X_6 + 326.67$, where X_6 is the averaged mechanical impurities concentration in the mine water. Calculations showed that reducing the concentration of mechanical impurities in mine water from 17 to 4 g/l would decrease the annual operating costs of the Udachny underground mine's main drainage section pumps by 100 million rubles.

Keywords

diamond mining, underground mine, PJSC ALROSA, Udachny mine, mine drainage, section pumps, wear, groove seals, mechanical impurities, operating efficiency

For citation

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ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Научная статья

Оценка влияния твердой фазы шахтных вод на эффективность секционных насосов при разработке месторождений кимберлитовых руд

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Аннотация

Несмотря на принятые нововведения в горно-обогатительных комбинатах АК «АЛРОСА» (ПАО) в рамках обновленной стратегии по экономическому развитию, практика свидетельствует, что за последние несколько лет существенно возросли затраты на эксплуатацию секционных насосов главного водоотлива подземного рудника «Удачный». Такому росту затрат мог способствовать заметный рост концентрации механических примесей в шахтных водах. Настоящая работа посвящена комплексной оценке влияния концентрации механических примесей в шахтных водах на эффективность секционных насосов главной водоотливной установки подземного рудника «Удачный» для технико-экономического обоснования проходки дополнительных наклонных осветляющих резервуаров. Поставленная цель достигается путем проведения визуальных, аналитических, статистических и других видов исследований по установлению степени влияния концентрации механических примесей в шахтных водах на ряд эксплуатационных показателей секционных насосов водоотливных хозяйств подземных кимберлитовых рудников. Комплексными исследованиями доказано, что концентрация механических примесей в шахтных водах является ключевым фактором, определяющим межремонтный ресурс и электропотребление насосного оборудования. Межремонтный ресурс секционных насосов главной водоотливной установки подземного рудника «Удачный» может быть рассчитан как линейная функция их подачи на момент вывода в капитальный ремонт, изменение которой с высокой степенью достоверности описывается эмпирическим выражением $Q = -7{,}5X_6 + 326{,}67$, где X_6 – усредненная концентрация механических примесей в шахтных водах. Расчетным путем установлено, что снижение концентрации механических примесей в шахтных водах с 17 до 4 г/л позволит уменьшить годовые затраты на эксплуатацию насосного оборудования главной водоотливной установки рудника «Удачный» на 100 млн рублей.

Ключевые слова
добыча алмазов, подземный рудник, АК «АЛРОСА» (ПАО), рудник «Удачный», водоотлив, секционные насосы, износ, щелевые уплотнения, механические примеси, эффективность эксплуатации

Для цитирования
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Introduction

During the pandemic many domestic mining companies faced sales problems.The above was also true of ALROSA diamond-mining company (hereinafter the Company), whose main production facilities are located in the Mirny district, Western Yakutia. While the demand for industrial and gem-quality diamonds is decreasing, the Company is actively implementing a variety of technological and technical solutions aimed at reducing the costs of mining and processing of rough diamonds as part of its updated economic development strategy.

Innovations implemented at the mining and processing divisions have had a positive effect on the Company's financial position to a great extent. However, at the same time the costs of certain mining process stages continued to grow. The main drainage of the Udachny underground mine is part of such special cases in the mining process flow sheet.

A significant share of the costs of mine drainage pumping equipment (centrifugal section pumps) operating is related to overhauls and electricity consumption. Fig. 1 shows that over the past six years, the costs in these items increased more than 2 times. Thus, there is an urgent need to establish the reasons for such growth of the costs.

The appreciable growth in the concentration of mechanical impurities in mine waters promotes hydro-abrasive wear of the liquid end parts, mainly the impeller groove seals (hereinafter groove seals). This can lead to premature deterioration of the pumping equipment performance [1, 2] and can considerably increase the costs.

The adverse impact of abrasive fluid flow on pumping equipment has been noted in historical studies [3–5].

High concentration of mechanical impurities in the pumped out mine water is caused by intensive pollution of drainage routes, along which the mine water moves from the mining levels to the sump galleries.

The main pollution sources are the rock mass, spilled from the conveyors and thickened sludge-slurry, spilled during its LHD hauling from sumps and clarifying working-reservoirs and hoisting to the surface.

At the same time, studies [6, 7] have shown that section pumps often fail due to extensive cavitation damage of the liquid end parts in the process of underground mining.

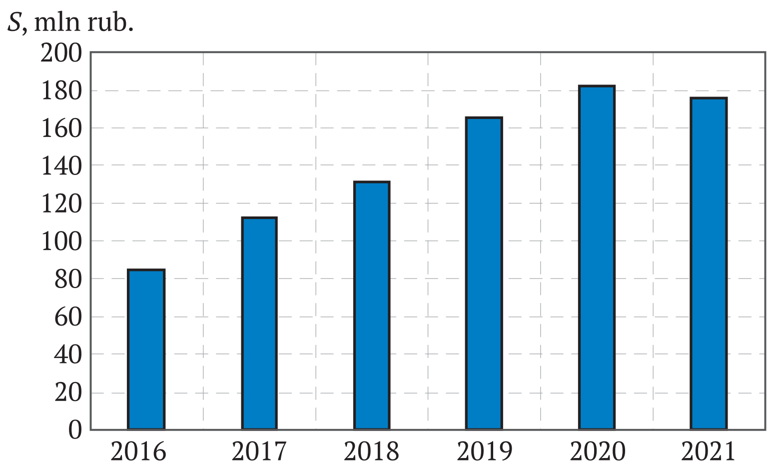


Fig. 1. The Udachny underground mine drainage pumping equipment operating costs by year

Certain papers [8, 9] have demonstrated activation of adhesion wear of section pump casing and rotor parts, typically if the maximum radial clearance in the groove seals has been attained.

The mine water pumped out by the pumps is mainly characterized by high mineralization and pH in the vicinity (above or below) of 7 [10].

In this connection, in the case of sufficient aggressiveness of mine water to metal, metal corrosion of the section pump liquid end parts can occur [11].

The above-mentioned studies supported to the conclusion that the decrease in the durability of the pumps liquid end parts in underground mines and coal mines was caused by complex multifactorial damage. This was due to the complex impact on the metal of hydroabrasion, corrosion, cavitation, and adhesion types of wear. The impact of each of these damaging processes depends on hydrogeological and mining conditions of the specific developed mineral deposit.

The operation services of the enterprise aim to achieve a considerable reduction of solids content at the outlet of the drain sumps of the Udachny underground mine's main drainage (from 17 to 4 g/l). A further aim is to achieve effective dewatering of sludge-slurry deposits via sinking additional inclined clarifying working-reservoirs with a total useful capacity of 7.500 m^3 (Fig. 2). However, the technical solutions implementation bottleneck is due to very high capital costs of about 340 million rubles.

This study is aimed at the integrated assessment of the impact of the concentration of mechanical impurities in mine water on the performance of the Udachny underground mine main drainage section pumps, as well as a feasibility study of sinking additional inclined clarifying working-reservoirs.

The target goal was achieved by means of visual, analytical, statistical, and other research methods to determine the impact of mechanical impurities concentration in mine water on performance indicators of section pumps of the Company's underground mines.

The study subject was section pumps of drainage facilities of the Company's underground mines.

Research techniques

The study of the Udachny underground mine's main drainage section pumps groove seal wear (the JSH-200 and NTsS(K) 350-1100 pump models)

The findings of numerous examinations of the worn-out groove seals showed that they were subject to hydroabrasive wear. This was evidenced by the peculiar waves on the outer surfaces of the impellers and the inner surfaces of the sealing rings, caused by vortex motion of the mine water polluted with mechanical impurities (Fig. 3, *a*–*c*). The largest mechanical impurities at an angle close to the normal, strike the metal causing its deformation in the form of dents and swellings. Smaller mechanical particles moving tangentially, cut the metal layer and the formed swellings [12].

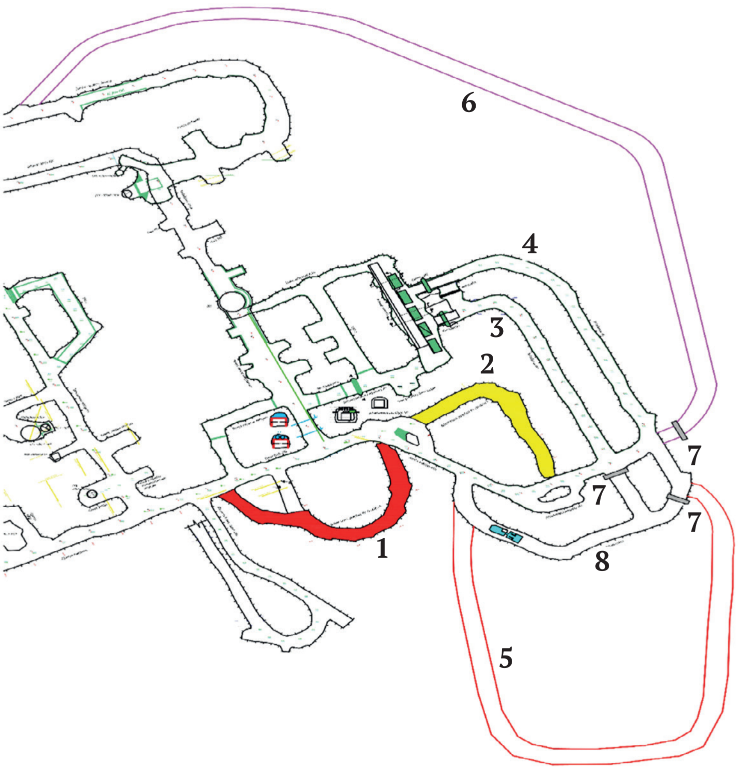


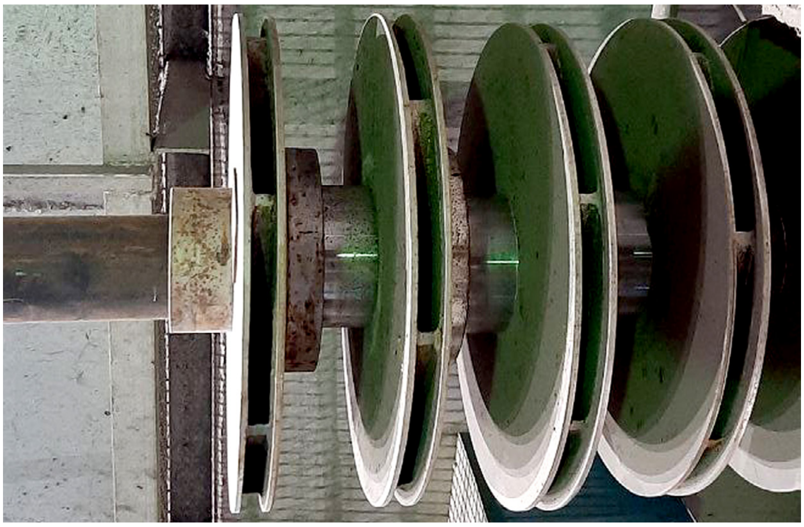
Fig. 2. Proposed main drainage system:
1 – clarifying working-reservoir #3; *2* – clarifying working-reservoir #4; *3* – drain sump #1; *4* – drain sump #2;
5 – design clarifying working-reservoir #5; *6* – design clarifying working-reservoir #6; *7* – bulkheads; *8* – slurry clarifier

The greatest damage to the metal from contact with mechanical impurities was observed in sites of corrosion, developed on the surfaces of the groove seal parts in the form of local spots (Fig. 4). The corrosion film formed on the parts surfaces is very sensitive to abrasion by mechanical impurities [13].

To a lesser extent, adhesive damage was observed in the failed groove seals. This damage manifested itself in a decrease of the thickness of the impellers collars and sealing rings partially or on the whole surface due to the rubbing of parts against each other (Fig. 5, *a*, *b*). This type of wear is a natural result of critical axial displacement of the rotor in the examined section pumps. This can be caused by the uneven distribution of pressure in the side grooves of the stages due to reaching the limit wear of the groove seals in the hydroabrasive-corrosive working medium. It should be noted that this type of mechanical wear in the section pumps liquid end parts usually indicates an emergency condition of the pumping equipment.

No cavitation wear of groove seals of the inspected pumps was observed. This is explained by their operation with the suction line back pressure. The back pressure ensures that the pump inlet pressure is higher than atmospheric, thus hindering cavitation phenomena development.

The visual inspections of the failed groove seals evidenced that hydroabrasive wear was the prevailing type of their surface wear. This wear was more intensively manifested at the spots of corrosion film formation.



a

b

c

Fig. 3. Hydroabrasive wear of the impeller groove seals:
a – impeller collars; *b*, *c* – sealing rings

Fig. 4. Corrosion film on the surface of the worn impeller collar

Fig. 5. Adhesion wear of impeller grooves and disks

Study of wear of underground diamond mines' section pumps

The overhaul periodicity of section pumps, depending on the intensity of hydroabrasive-corrosion wear of the groove seals surfaces for a given period of time, is conditioned by the effect of the following internal and external environment factors:

- Factors responsible for the abrasive flow velocity: *section pump nominal delivery* X_1 *and delivery head* X_2, *electric motor nominal speed* X_3, *nominal diameter of the impeller groove* X_4, *nominal radial clearance in the groove seals* X_5;
- Factors responsible for the physical-and-mechanical characteristics of the mine water solid phase: *average concentration of mechanical impurities* X_6, *nominal diameter of an abrasive particle* X_7, *its hardness* X_8, *and density* X_9;
- Factors responsible for the mechanical impurities abrasion resistance of the part surfaces: *metal nominal hardness* X_{10}, *averaged mineralization* X_{11}, and averaged mine water pH X_{12}.

The author selected the most significant factors based on the theoretical principles of fluid pumping, hydrogeological conditions of kimberlite ores underground development, and failures of the examined section pumps.

X_1 and X_2 factors were selected from the first group of factors for further study of the hydroabrasive-corrosion wear. The selection of the X_1 factor was due to the fact that it is the best-known parameter which characterizes the kinematics of water movement in a pump liquid end. In addition, in accordance with the theory of hydrotransport, the factor can be considered as a function of the design parameters of the pumps, affecting the speed of the pumped flow, i.e., X_3–X_5 factors. It is for this reason that the above three factors were not taken into account in the further research. X_3 factor exclusion was also due to its value in most of the section pumps in the Company's underground mines was the same, at rated 1.450 rpm.

X_2 factor selection was based on the findings of the visual inspections of the pumps' groove seals. The visual inspections of the section pumps showed that in most cases the hydroabrasive wear of groove seals of the pump stages was almost the same. Theoretically the mechanical impurities have the greatest adverse impact on the parts of the initial stages due to their sharp angular shape. This shape becomes more rounded as they move from the first stage to the last. At the same time the rounded solid particles (grains) in the final stages move at greater fluid pressure compared to the sharp grains in the initial stages. Thus, the impact on a metal of a rounded particle in the higher pressure zones should be compared to its initial sharp shape impact.

From the second group of factors, only X_6 factor was selected. With regard to the other physical and mechanical characteristics of the solid phase in mine water pumped from underground kimberlite mines (the other factors of the group), their values are almost the same. It is for this reason that these factors were not considered in the further studies.

The liquid end parts of the section pumps operating in the Company's underground mines' drainage systems are mainly corrosion-resistant. Evidence of this is their identical operating characteristics, including the steel strength properties. For this reason X_{10} factor was excluded from consideration. Practice shows that mine water pumped from underground diamond mines in terms of its chemical activity to metal is either slightly alkaline or slightly acid brine, depending on the specific mine. Based on the above information, X_{11} and X_{12} factors were selected from the third group of factors.

The performed review and analysis allowed stating the average overhaul life of section pumps T can be represented as a function of the following five factors selected:

$$T = f(X_1, X_2, X_6, X_{11}, X_{12}). \quad (1)$$

The impact of each of the selected factors was determined by means of statistical research.

Statistical studies on the selected factors impact on the frequency of section pumps overhauls

The statistical studies to assess the impact of the selected factors on the *T* indicator were performed as follows. The weighted average values of the parameters (see formula (1)) were entered into MS Excel spreadsheets, which subsequently formed the correlation fields. Equations of linear regression and their confidence parameters were determined by linear-trend approximation (Fig. 6, *a*–*e*). Then we checked the equations for adequacy on the basis of Fisher's ratio test (*F*-test) at the confidence level $g = 0.05$ in the Data Analysis software package.

The confidence factors of the regression equations obtained testified that the *T* value was mainly governed by X_2 and X_6 factors. These correlation and regression analysis findings are adequate, since the *F*-significance parameter values in both cases amounted to 0.03. Thus, the studies have confirmed the adverse impact of the mine water solid phase on the frequency of overhaul life of section pumps in the Company's underground mines.

Although the values of the confidence factors of the regression equations where X_{11} and X_{12} factors are function arguments are not very high, it is clear that both these factors also have certain effects on the overhaul life of the Company's underground mines' pumping equipment.

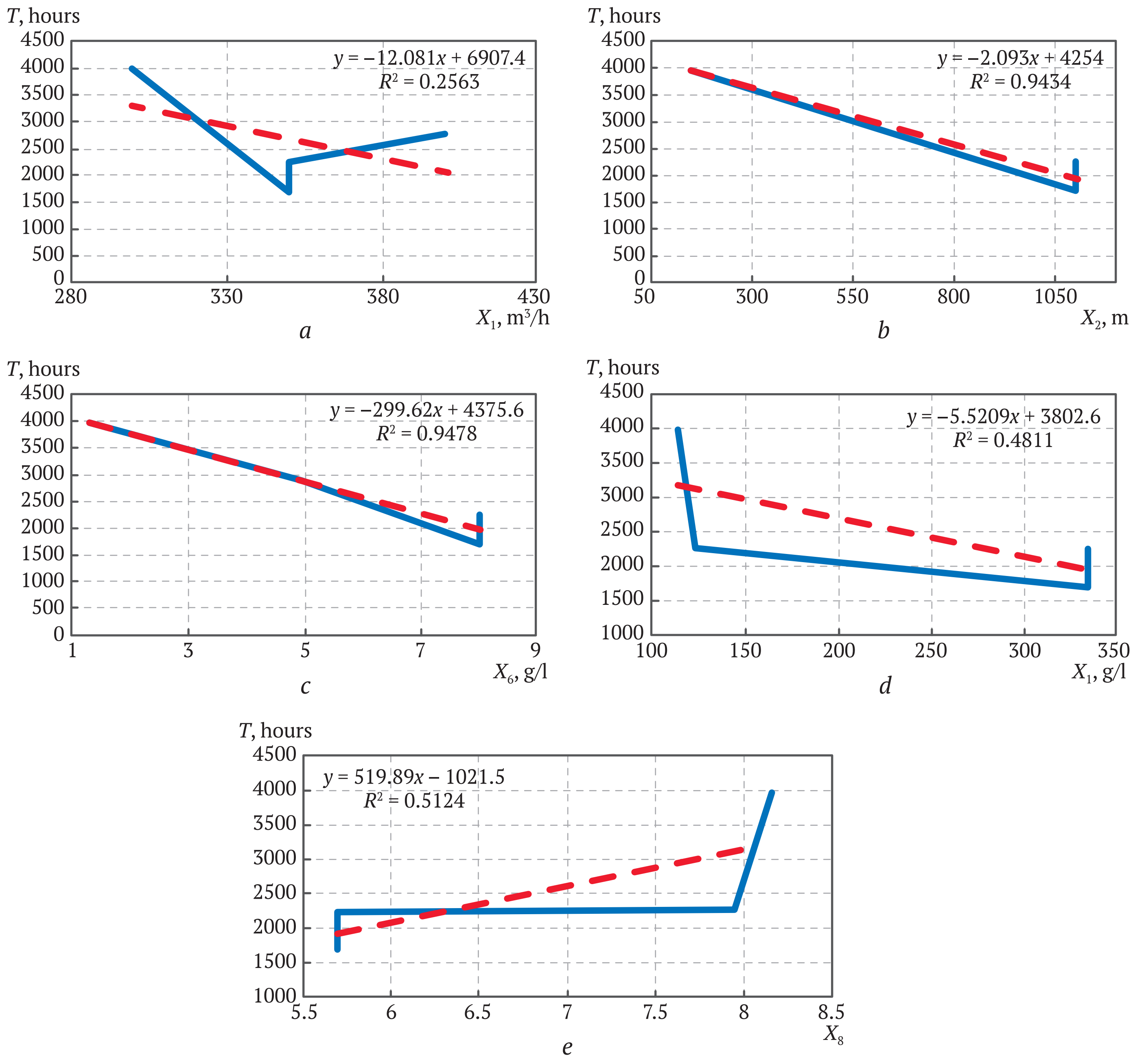


Fig. 6. Average overhaul life of section pumps as a function of rated pump delivery (*a*), rated pressure head (*b*), averaged concentration of mechanical impurities (*c*), averaged mineralization (*d*), and averaged mine water pH (*e*)

It is interesting that the average overhaul life T_r of the section pumps, used in the main drainage system of the Udachny underground mine, decreased to 1625 h, while X_6 factor increased more than two times (from 7 to 17 g/l) (Fig. 7, *a*). At the same time, evaluation by means of the formula obtained from the statistical research (see Fig. 6, *c*), at X_6 = 14 g/l, gave the projected overhaul life value below 200 hours (Fig. 7, *b*).

Due to such inconsistency in the results of the studies, the author conducted additional research.

Reasons for the difference between the actual and evaluated values of the average overhaul life of pumping equipment depending on the concentration of mechanical impurities in mine water

One of the criteria for the removal of a section pump for overhaul is a considerable decrease of its delivery rate (by 30% of the nominal value and more) as a result of increasing the annular slot.

Evaluations (Fig. 8) using the technique described in [14] showed that radial clearance (h) in the section pump groove seals increased by more than 1 mm, their lower limit at operating time *t* of 2250 h, X_6 = 7 g/l; at operating time *t* of 1750 h, X_6 = 9 g/l; at operating time t of 1000 h, X_6 = 16–17 g/l. It should be recalled that the initial radial clearance in the groove seals of the Udachny underground mine's section pumps was about 0.65 mm.

The difference between the actual and evaluated values of the pumping equipment average overhaul life proved to be particularly strong when X_6 = 16–17 g/l.

Thorough analysis of the Udachny underground mine's main drainage pumps operating practice showed that the actual value of Tr parameter did not sufficiently decrease at X_6 = 16–17 g/l when a pump was removed for overhaul after reaching the lower delivery rate *Q* as compared with the previous years (Fig. 9, *a*). Fig. 9, *b* demonstrates that parameters *Q* and T_r are strongly correlated with each other, as indicated by the resulting confidence factor.

The Company argued that the reduction of the delivery rate *Q* in the period of 2019–2021 was due to the need to prevent an excessive number of overhauls of pumps in connection with significant increase in X_6 factor. The correlation and regression analysis showed the strong correlation between the above-mentioned parameters (Fig. 10).

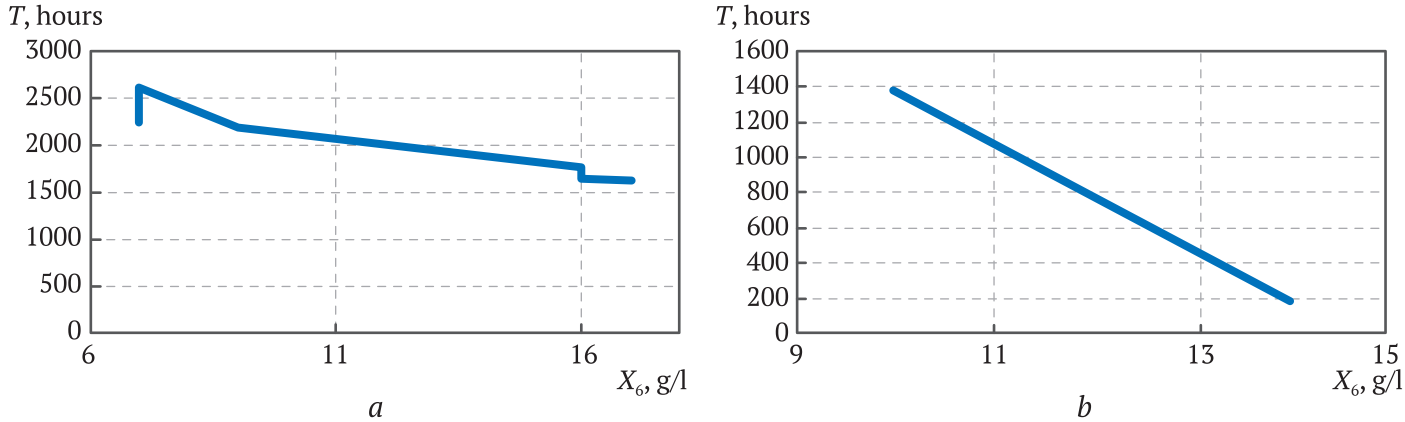


Fig. 7. Comparison of actual (*a*) and evaluated (*b*) values of overhaul life depending on the concentration of mechanical impurities in mine water

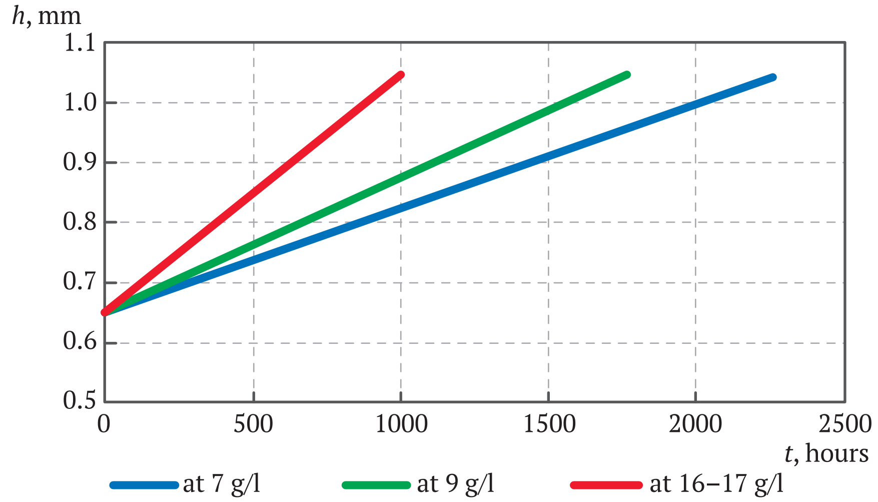


Fig. 8. Radial clearance in groove seals depending on section pump running time

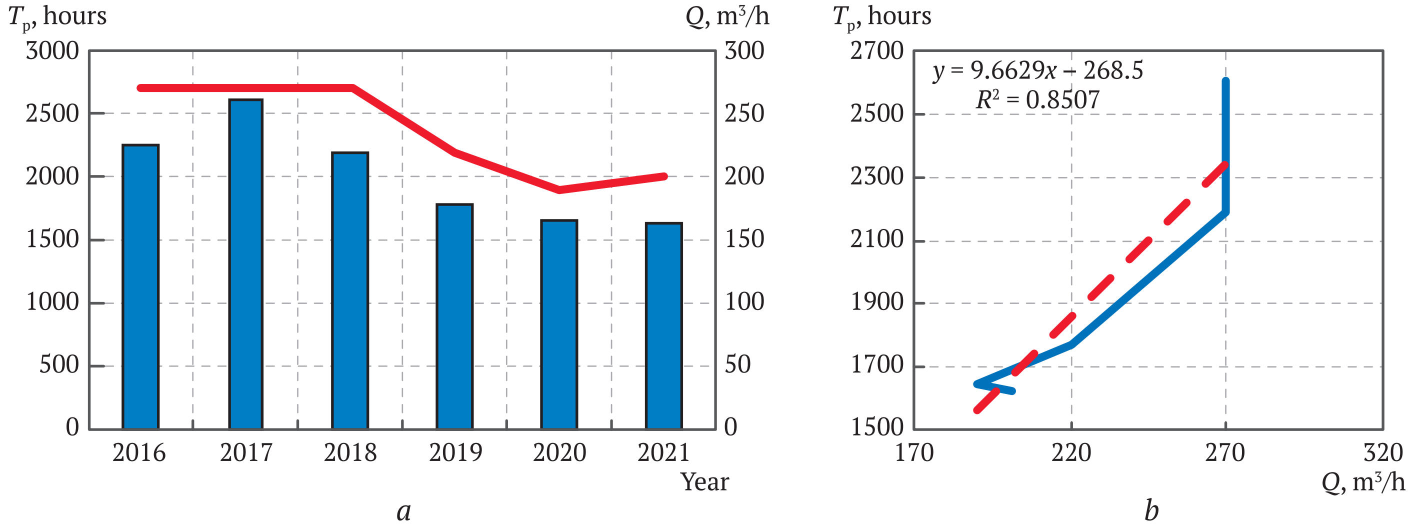


Fig. 9. Time history of section pump average overhaul life and its delivery rate at the moment of pump taking-down for overhaul by year (*a*) and dependence between these parameters (*b*)

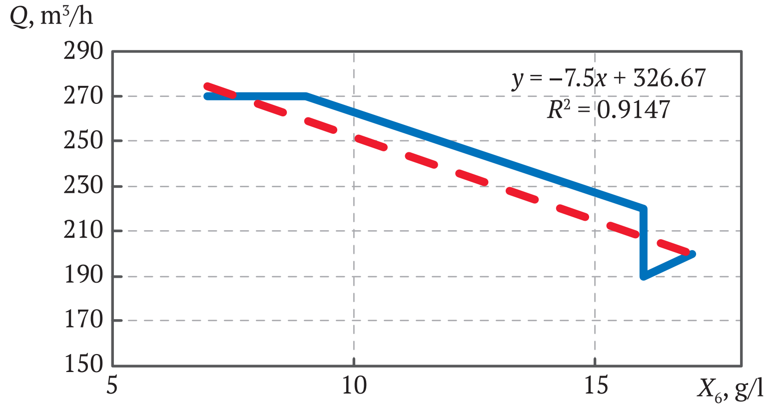


Fig. 10. Section pump delivery rate at the moment of taking-down it for overhaul as a function of averaged concentration of mechanical impurities in mine water

Thus, the overhaul life of the main drainage's section pumps can be calculated as a linear function of their delivery rates at the moment of removal for overhaul. This function is confidently described by empirical expression $Q = -7.5X_6 + 326.67$.

Assessment of energy performance of section pumps when pumping abrasive mine water flow

The laboratory research (Fig. 11, *a*) undertaken according to the technique described in [15] showed that power consumed by centrifugal one-stage pump *P* decreases smoothly, at a rate of 13 %, with a considerable decrease in pump delivery *Q* (by 26 %) due to the liquid end parts wear. At the same time Fig. 11, *b* demonstrates that such a decrease in the delivery rate *Q* is accompanied by significant drop in the pressure head *H*.

In turn, the section pump delivery rate drop by 20–23 % from its nominal value due to intensive wear of groove seals leads to the drop of consumed power by 6.5 % (Fig. 12, *a*). Such a smooth decrease of the power consumed by the section pump at different delivery rates as compared with the single-stage pump can be explained by the relative stability of the pressure head value (997–1008 m). This is caused by the low wear of impeller blades, responsible for the developed delivery rate and pressure, in connection with small size of the pumped solid particles (Fig. 12, *b*). The bulk of mechanical impurities (80–85 %) is represented by −0.05 mm size class.

According to [16] the quantity of mechanical impurities ε, contacting with impeller blades of centrifugal pump, directly depends on their size *d*:

$$\varepsilon = 0.4\sqrt{\frac{0.75}{1+0.35\cdot\dfrac{\rho_{sol}}{\Delta\rho}\cdot\dfrac{D}{d}}}, \qquad (2)$$

where ρ_{sol} – is density of the mechanical impurities, $\Delta\rho$ – is difference of densities of the mechanical impurities and pure water, *D* – is impeller diameter, *d* – is size of solid particle.

In other words, the smallest solid particles are carried away by mine water flow, and do not comeinto contact with impeller blades.

Thus, the pumping of mine water by means of section pumps with worn-out groove seals takes considerably more time when compared with a new or overhauled pump, while its consumed power decreases only slightly. This ultimately leads to significant total increase in power consumption. All this testifies to inexpediency of long-term operation of section pumps at low delivery rates in terms of energy performance.

Findings Discussion

Our research confirmed the adverse impact of intense hydroabrasive wear on the groove seals upon the performance of the section pumps. Fig. 13 shows that the impact of X_6 factor on the total costs in the main cost items S (overhaul and consumed power costs) of the section pumps of the drainage facility can be confidently described by the following empirical expression: $S = 7.6835X_6 + 49.577$. This expression shows that a reduction in the concentration of mechanical impurities in mine water from 17 to 4 g/l leads to a reduction in

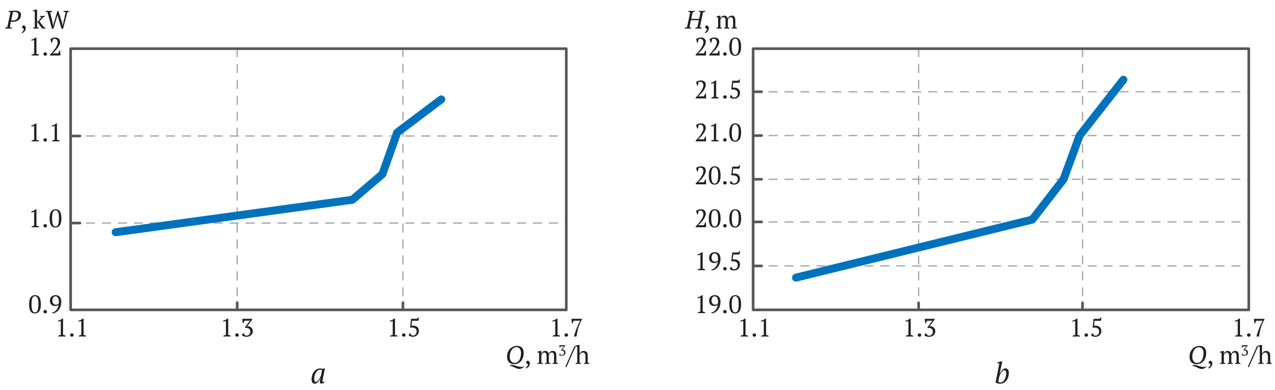


Fig. 11. Consumed power (*a*) and pressure head (*b*) as a functions of a single-stage pump delivery rate

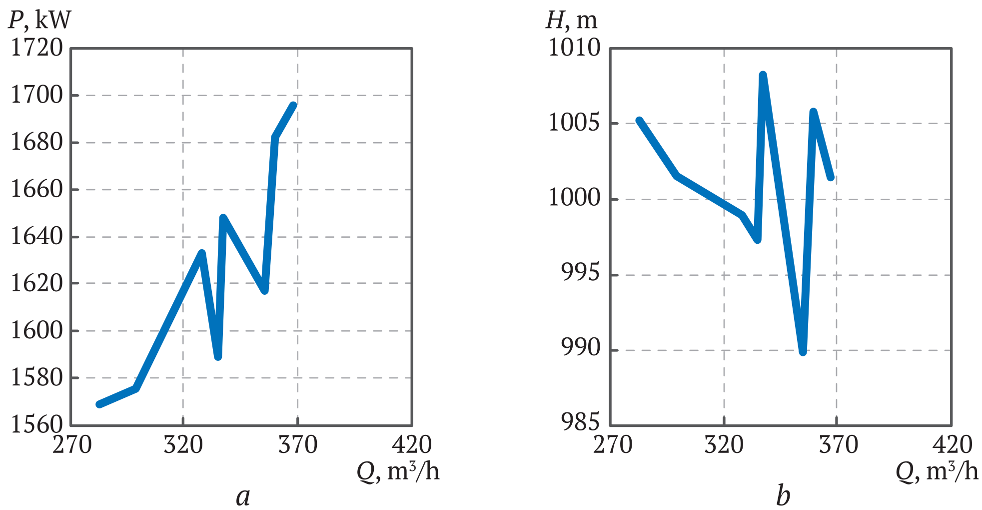


Fig. 12. Consumed power (*a*) and pressure head (*b*) as a functions of a section pump delivery rate

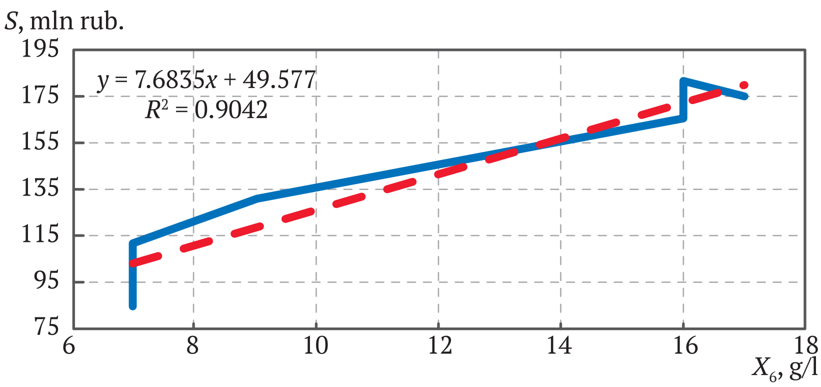


Fig. 13. Total pumping equipment overhaul costs and power consumption as the functions of averaged concentration of mechanical impurities in mine water

the annual operating cost of the Udachny mine's main drainage pumps by 100 million rubles.

Taking into account the expected economic effect of reducing solid phase concentration in mine waters, the capital investments of 340 mln rubles in sinking two design clarifying working-reservoirs will be repaid for less than 3.5 years.

Conclusion

In view of the above the following key conclusions were drawn:

1. The overhaul life of the Udachny underground mine's main drainage section pumps can be evaluated as a linear function of their delivery rates at the moment of their removal for overhaul. This function can be reliably described by the empirical expression $Q = -7.5X_6 + 326.67$, where X_6 is the averaged mechanical impurities concentration in the mine water.

2. Reducing the section pump delivery rate by 20–23 % of its nominal value due to intensive wear of groove seals leads to a drop in consumed power by 6.5 %. The smooth decrease in power consumed by the section pump different delivery rates is due to the relative stability of the pressure head value (997–1008 m). This is caused by low wear of impeller blades due to small size of the bulk of pumped solid particles (−0.05 mm size class).

3. The evaluation showed that a reduction in the concentration of mechanical impurities in mine water from 17 to 4 g/l leads to a reduction in the annual operating costs of the Udachny underground mine's main drainage section pumps by 100 million rubles. Thus, the payback period for sinking two design clarifying working-reservoirs aimed at achieving a significant reduction in solid phase concentration in mine waters will be less than 3.5 years.

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