Geological Quarterly, 2024, 68: 16
DOI: http://dx.doi.org/10.7306/gq.1744

Improvement of maintenance and repair work on technological wells in the conditions of the "North and South Karamurun" deposit, Kazakhstan

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Omarov, A., Yussupov, K., Yeluzakh, M., Myrzabek, G., 2024. Improvement of maintenance and repair work on technological wells in the conditions of the "North and South Karamurun" deposit, Kazakhstan. Geological Quarterly, 68: 16; https://doi.org/10.7306/gq.1744

Associate Editor: Beata Jaworska-Szulc

In the complex and constantly changing area of uranium mining, the Republic of Kazakhstan is a world leader. Colmatation deposits adjacent to filters cause wells to lose efficiency over time, so periodic maintenance and repair are required to solve these problems. Our research aims to identify the most effective ways to improve well productivity with the development of science-based recommendations to help plan work in the conditions of the "North and South Karamurun" uranium field, Kazakhstan. The study involved observation, analysis, comparison, and synthesis. The processes of different types of repair and restoration work at the deposits were monitored, and the results obtained were analysed and compared, to determine which were the most effective. Units such as the XRVS Airlift Pumping unit, Wellbore pneumatic wellbore drilling unit, Mobile ammonium bifluoride chemical treatment unit, BA-15V drilling units, and 3A3 prospective drilling unit were analysed. Recommendations for enhancing pumping technology or replacing components were developed for each unit. Extending XRVS airlift pumping duration enhanced efficiency by 40% and improved reliability and radiation safety. Installing a pump with a capacity of 30 m^3/hour or higher for the mobile wellbore washing unit helped handle heavy sand fractions effectively.

Key words: uranium mining, *in situ* leaching, colmatation, filters, productivity.

INTRODUCTION

Uranium mining is important for Kazakhstan, both economically and strategically. Kazakhstan is one of the world's leading producers of uranium, possessing abundant reserves and high-grade deposits. The uranium sector contributes substantially to the country's GDP and export revenues, providing employment opportunities and supporting economic development. However, the sector faces challenges, particularly falling productivity, which can be attributed to various factors. These include aging infrastructure, technological limitations, environmental concerns, and market fluctuations affecting uranium prices. Additionally, geological complexities, such as deeper ore deposits and challenging extraction conditions, pose operational challenges for mining companies. Addressing these difficulties is crucial for maintaining Kazakhstan's position as a key player in the global uranium market and ensuring the sustainable growth of the uranium mining sector. Implementing innovative technologies, investing in infrastructure upgrades, improving regulatory frameworks, and enhancing environmental sustainability measures are among the strategies needed to overcome these challenges and sustain the sector's growth in the long term.

The search for effective physical and chemical methods of well repair and maintenance operations (RMO) to increase the flow rate and overhaul cycle at uranium mining enterprises is an important task for the uranium industry in Kazakhstan (Deryaev, 2023a). The importance of solving these issues is increasing since the productivity of stripped blocks is decreasing, and the fleet of operating wells is growing.

During the operation of technological wells, their flow rate or injectivity decreases (Kondrat and Matiishyn, 2023). This is caused by the deposition of colmatitic sediments, clay particles, and solid impurities on filters and in near-filter zones, left after the inefficient removal of drilling mud. Geochemical properties and the grain size distribution of ore-bearing rocks, filter design, the method of mud delivery and lifting, and various natural technogenic factors also influence the rate of well productivity reduction. All this requires measures to restore and maintain their productivity at the optimal level or the level achieved during their development. Various technological solutions are used to address the issue of the increasing decline in the efficiency of

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Received: January 5, 2024; accepted: March 14, 2024; first published online: May 17, 2024

process wells in uranium mining by the *in situ* well leaching method (Koroviaka et al., 2023). Zhang et al. (2022) applied oxidative uranium leaching using micro-nano bubbles and ozone. As a result of this experiment, it was established that this method accelerates the rate of oxidative leaching of uranium in sandstone-type deposits. Asghar et al. (2020) experimentally studied the effect of neutral leaching of uranium with oxygen and carbon dioxide on the geochemical characteristics of ore in the Zinda Pir deposit, Pakistan. It was found that the use of this compound increases the effective recovery of uranium ore.

Sun et al. (2021) described alkaline, neutral, and acid leaching of uranium, evaluated their impact on the environment, and proposed ways to remediate soils. De Lurdes Dinis and Fiuza (2021) studied groundwater contamination during uranium mining and reviewed the current technologies for their treatment. They identified the most profitable technologies for groundwater remediation, as well as the alternative solutions proposed. These include the conversion of radionuclides into a harmless form, reducing the formation of secondary waste. Sofranko et al. (2020) developed a methodology for mining uranium ore from the Kuriskov deposit in eastern Slovakia, describing the mining and geological conditions of the deposit, assessing the ore reserves, and studying the prospects for the development of the Slovak energy industry.

These studies do not address the specifics of increasing the efficiency of process wells, nor do they conduct a comparative analysis of the technical indicators of water shut-off operations at specific uranium mining companies. There is no planning for carrying out RMO in various conditions of uranium ore production and evaluation of the economic component of these measures. Therefore, we aim to analyse the factors affecting the effectiveness of RMO in the conditions of the “North and South Karamurun” deposit and to develop the most effective science-based recommendations for planning RMO. For this purpose, it is necessary to solve the following tasks: to compare and evaluate the effectiveness of different water shut-off methods in the context of the “North and South Karamurun” deposit and to develop a practical framework for planning and implementing cost-effective RMO at uranium mining enterprises.

MATERIALS AND METHODS

Our research is based on observational methods focused on workover operations to restore well productivity in the field “North and South Karamurun”. It involves analysis and comparison of technological, economic, geological, and hydrogeological factors affecting the effectiveness of RMO. The synthesis of the data obtained is aimed at determining science-based recommendations for the selection of the most effective types of RMO in their planning and budgeting.

The study was conducted at the uranium mining enterprise JSC National Atomic Company (NAC) Kazatomprom within the technological wells of the “North and South Karamurun” field operated by LLP “RU-6" in the Republic of Kazakhstan. Monitoring activities aimed at restoring and enhancing the productivity of these wells were conducted from July to December 2022 across various production fields. A total of 412 technological wells that penetrate deposits 2, 3, 20, and 9 were subjected to test observations. The research was conducted in three distinct stages.

In the first stage, monitoring took place of RMO types used on pumping and injection wells at Karamurun mine under different regimes. Our method of observation allowed determination of how much time it takes to pump by XRVS airlift pumping and wellbore pneumatic drilling unit, mobile chemical treatment unit, and mobile wellbore washing unit (Oryngozhin et al., 2020). Similarly, data concerning the duration of complex well treatment by the prospective drilling unit 3A3 and the 1BA-15V drilling machine, which includes flushing, chemical treatment, repeated flushing, and airlift pumping, have been obtained (Verkhoturov and Sabigatulin, 2019). The concentration of sulphuric acid and ammonium bifluoride needed to be pumped into the well depending on the content of impurities and colmatants was determined. The test observations addressed the duration of arrival and departure for the shift, installation, pumping, downtime, and dismantling.

In the second stage, a comparative analysis of the technical and economic indicators of the RMO on technological wells of the “North and South Karamurun” field was carried out. Also, geological, hydrogeological and geotechnological factors affecting the effectiveness of the RMO in these conditions were analysed. Reasons for the decrease in productivity during in-situ borehole leaching were studied. The number of hours spent on moves, mounting and dismounting operations, downtime (waiting for installers, supplies, equipment adjustment), and pumping of wells was determined through processing of the data received. The duration of each type of RMO was calculated, and subsequently, the total cost of the methods of RMO at the mine site was determined. By analyzing the results of observations and the unique features of the “North and South Karamurun” field, we identified ways to increase productive time per shift and minimize financial costs. Specifically, we discovered the significant influence of the duration of good pumping and the concentration of chemical solutions on their productivity.

In the third stage, by synthesizing the data obtained, science-based recommendations were developed to increase productivity and economic indicators of the technological wells. Adjustment of the regulations for each type of RMO and balancing their number were proposed. The advantages and disadvantages of each type of work were identified, and alternative options and means of modernization of existing technologies were suggested. On this basis, the most effective and profitable RMO for pumping and injection wells was determined.

RESULTS

“North and South Karamurun” is a large uranium deposit in the Kyzylorda region of the Republic of Kazakhstan, which is part of the Karamurun uranium ore district group. This includes such uranium deposits as North and South Kharasan, Irkol, and other smaller bodies. The depth of ore occurrence increases westwards from the Kazakh Shield towards the Caspian Sea and is associated with the central parts of the Meso-Cenozoic cover of the Shu-Sarysu and Syr-Darya synclinal troughs. “North and South Karamurun” has the maximum depth of occurrence among the ore bodies, which is 500–700 m and more. Mining at the deposit is also complicated by the following production and geological factors: a groundwater table at 10–15 m; the presence of significant amounts of fine-grained sand in the ore horizon; the presence of dispersed water-bearing layers; the presence of carbonate-bearing blocks in the ore-bearing rocks with up to 1.8% carbonate (with average content in the deposit being 0.5%); and undrained ore bodies themselves. The uppermost aquifer, where the groundwater depth is 10–15 m, is not isolated from the ore deposits by impermeable rocks, though there are also indications of other aquifers separated by impermeable deposits. The Karamurun uranium ore district has a high level of carbonate-gypsum deposits in the productive horizons, resulting in higher costs of sulphuric acid reagent treatment of wells. “North and South Karamurun”,

Table 1

Unit operation mode during RMO on RU-6 well

Name	Operation modes	Amount of machinery and auxiliary tools	
		brand	pcs.
XRVS Airlift Pumping	Well washing requires 3–6 hours Well pumping for 2–3 hours	XRVS 336 XRVS 346	10
Mobile Wellbore Washing Unit well washing	Wash and pumping time of wells – 5 hours		
Well processing with BA-15V drilling machine and prospective drilling unit	Well washing and pumping require 40–48 hours Well pumping for 20–24 hours Washing is conducted as follows: 1. Washing 2. Chemical treatment 3. Washing 4. Airlift pumping	KAMAZ truck chassis	2
Well washing with wellbore pneumatic drilling unit	Wash and pumping time of wells is 2 hours, depending on the number of tanks	URB-3A3.13 prospective drilling unit, BA-15 drilling unit	3
Supply and injection of sulphuric acid and BPA solutions to the well by a solution truck	Depending on the content of impurities and colmatants, 50 kg and above is injected with an appropriate concentration of acid	Based on ZIL and MAZ truck chassis	3
Sulphuric acid solution injection into the well through the piping system	Well pumping and injection from 30 g/l to 150 g/l depending on impurities and colmatants content	The fluid tank is placed on a cart	
Total			18

among all the deposits, has the highest level of carbonate. The geochemical and mineralogical composition of this deposit causes colmatation during its development.

The ore bodies lie at a great depth, which leads to an increase in the cost of RMO and a decrease in their quality. Mining of the ore is a lengthy process, which affects the increased wear of the wells and causes changes in the filtration properties of the ore bodies. Since the first mining operations at this deposit began in 1986, the previously used methods of advanced acid treatment led to gypsum colmatation of neighbouring technological blocks and the wells put into development in recent years (Yazikov et al., 2001). Various methods and units are used to carry out RMO at the mine. Table 1 shows the operation modes for each unit.

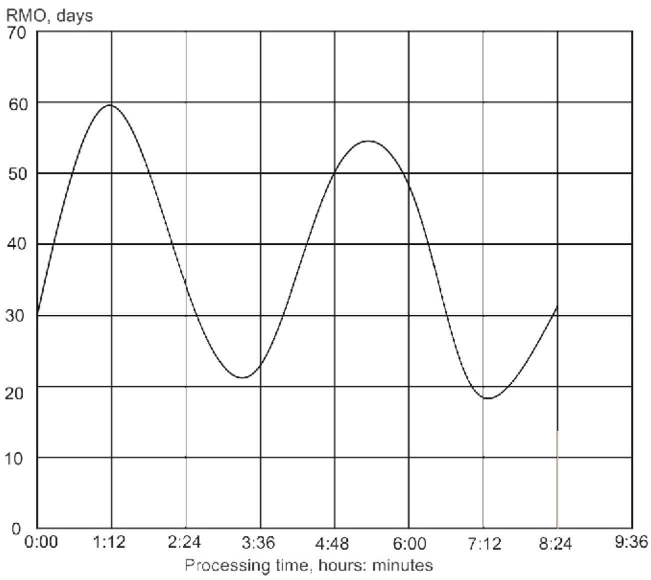


Fig. 1. Model dependence of RMO efficiency on the treatment duration (XRVS prospective drilling unit on pumping wells)

Based on a comparative analysis of the North and South Karamurun deposits (LLP "RU-6") and the uranium mineralization and other deposits of NAC Kazatomprom JSC located nearby, the most optimal technical and economic indicators of RMO were determined for the development of alternative methods of conducting the airlift pumping and chemical treatment with sulphuric acid. For this purpose, data were collected and processed as regards the change of inter-repair cycle (IRC) of pumping wells. There is a downwards trend in the model dependence of the effectiveness of the XRVS prospective drilling unit on pumping wells on the treatment duration (Fig. 1).

Moreover, the proportion of wells with low efficiency (less than 20-30 days) falls on treatments lasting less than 2.5 hours. Further increase in the pumping duration does not give a proportional effect, which is due to the effectiveness of the chemical treatment rather than the pumping. The factor of pumping duration from 3 to 4 hours for pumping wells is the most optimal by the ratio of the result to the cost of time. The model dependence of pumping wells RMO efficiency on XRVS prospective drilling unit treatment duration (specific efficiency) is shown in Figure 2.

As can be seen from the model dependencies, there are two "peaks" of effectiveness, with durations of about 1 hour and 4 hours. The "1-hour" peak is characterized by high IRC of wells and high efficiency in terms of the number of successful water shutoffs with a positive effect. This is partly explained by the fact that pumping is done in one trip of the tanker and there are no stops for pumping for transportation and discharging of solutions. Pumping from 1 to 4 hours is performed in several trips (stages) to the tanker, which is accompanied by pumping stops and, as a consequence, a reduction of efficiency. Pumping for about 4 hours was performed in the long-term treatment tank and shows a clearer picture of efficiency with high average IRC and high shares of effective RMOs. Further pumping times have no appreciable increase in efficiency. For pumping wells, there is a similar trend of decreasing RMO efficiency with pumping time. Figures 3–5 show the correlation between the efficiency of RMO and the duration of treatment on injection wells (the main share of treatments with poor results is with pumping for up to 2 hours).

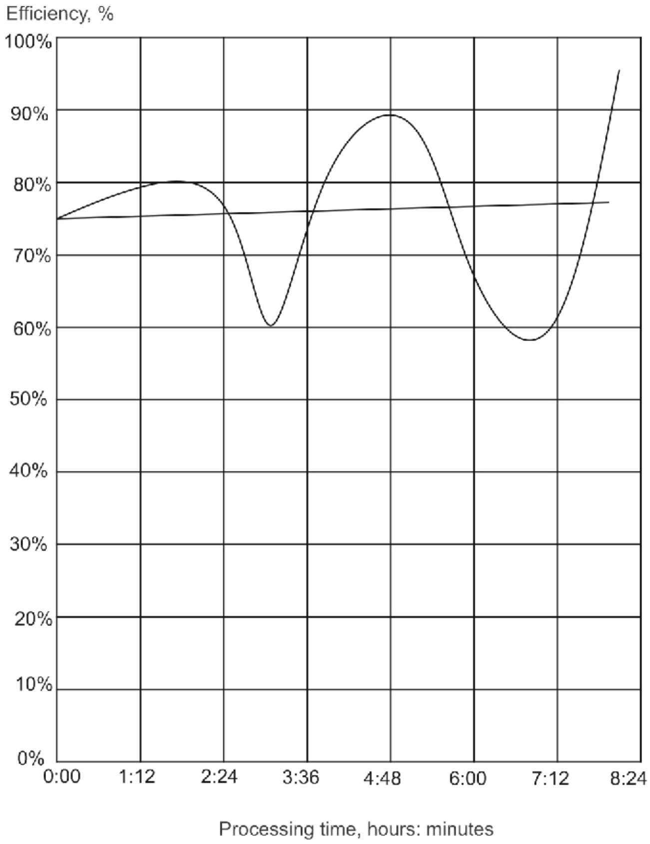


Fig. 2. Model dependence of pumping wells RMO efficiency on XRVS prospective drilling unit treatment duration (specific efficiency)

Based on model dependences, there are two "peaks" of efficiency for durations of about 1 hour and 4 hours. The "1-hour" peak is characterized by high well IRC and high efficiency in terms of the number of successful RMOs with a positive effect. Pumping for more than 2.5 hours was performed in the long-treatment reservoir and shows a less clear pattern of effectiveness with high average IRC and high proportions of effective RMOs. Further pumping times also show no appreciable increase in efficiency, with 5 and 6-hour pumping times having similar efficiencies to the 4-hour pumping. With XRVS prospective drilling unit airlift pumping, switching to continuous pumping will increase production time by an average of 40%, improve fail-safety, improve radiation safety of operations (discontinuation of solution transport), and prevent emissions of burned diesel fuel, as well as reduce the cost of RMO. Similar observations were made regarding air-pulse pumping (ASPT-M wellbore pneumatic drilling unit). Figure 5 shows the correlation between the efficiency of the RMO method and the treatment duration.

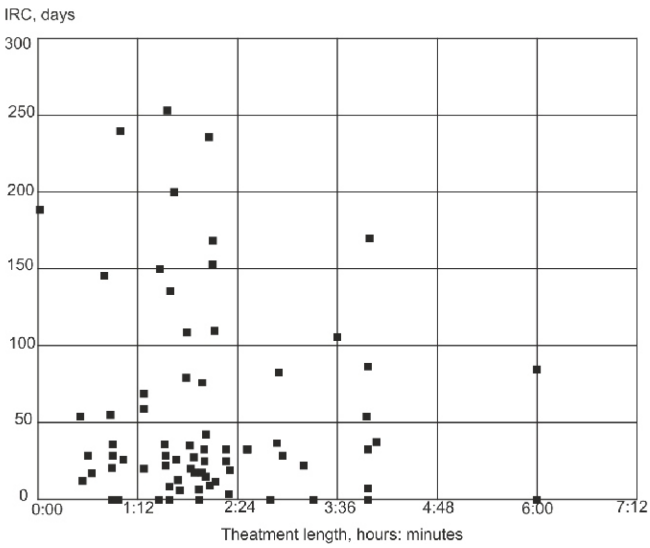


Fig. 3. Model dependence of pumping wells RMO efficiency on XRVS prospective drilling unit treatment duration

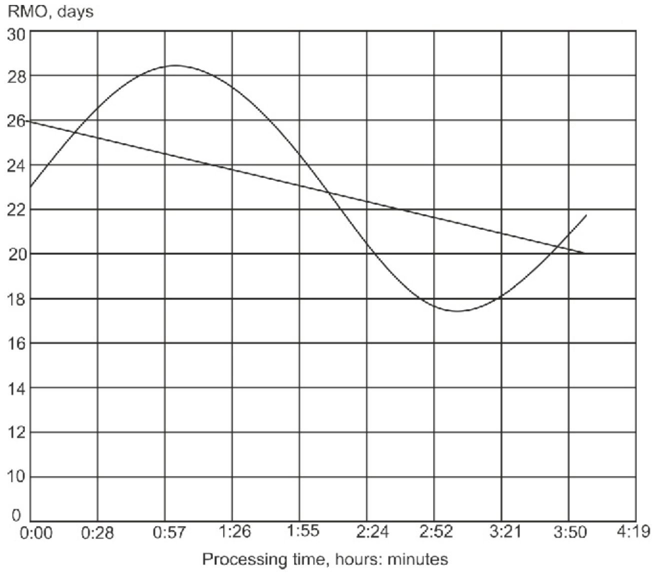


Fig. 4. Model dependence of pumping wells RMO efficiency on XRVS prospective drilling unit treatment duration (IRC)

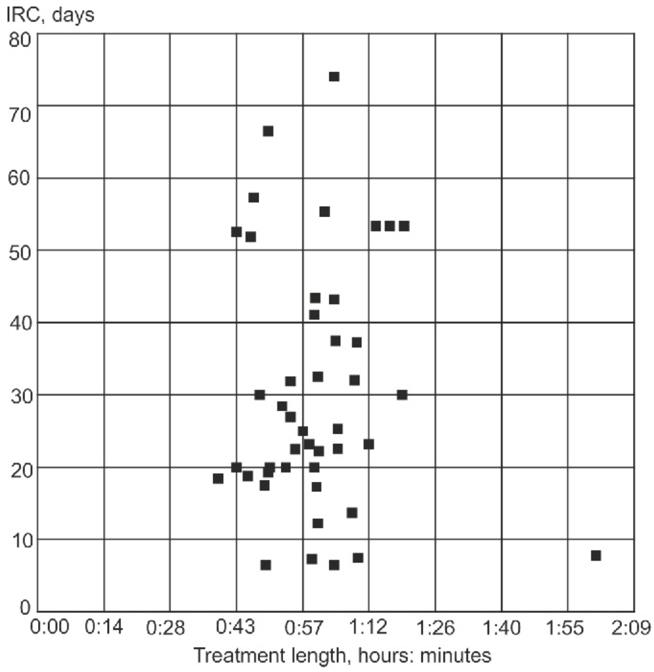


Fig. 5. Model dependence of RMO efficiency on the treatment duration (wellbore pneumatic drilling unit)

Table 2

Analysis of pumping efficiency and duration of injection wells pumping by the wellbore pneumatic drilling unit

No. of well	Pumping	IRC, days
Number of treatments	43	31
Number of inefficient treatments	0	0
Number of efficient treatments	43	31
RMO share that had no effect, %	0	–

Table 3

Results of borehole treatment with ammonium bifluoride solutions by the mobile chemical treatment unit

Parameter	Number of treatments	IRC, days	Perc. of PDP, %
Effective	14	55	70
Without positive effect	6	3	30
Total wells	20	39	100

The duration of treatment in this case is controlled by the amount of air in the compressed air cylinders and the amplitude of its variation is relatively low. For the majority of monitoring wells, it varies in the interval of 43 minutes to 1 hour and 15 minutes. In this case, the efficiency of RMO depends on the wells, not on the duration of pumping. Notably, the wellbore pneumatic drilling unit had no cases of failure to achieve the required pumping efficiency, i.e., all wells after pumping had injectivity growth and an average inter-repair cycle of around 31 days (Table 2).

In the case of pneumatic pulse treatment with the wellbore pneumatic drilling unit, it is suggested to assemble a tank on the trailer to collect the pumped solution. Equipped with the tank, the wellbore pneumatic drilling unit can perform pumping and draining of the process fluid independently, thus reducing downtime and RMO costs. It was determined that the best technical and economic indicators for the workover of injection wells in terms of efficiency/cost/overhaul cycle are of two types. These are airlift pumping by compressor with a duration of 1 hour, and the wellbore pneumatic drilling unit. After analysing mobile wellbore washing unit well flushing data, the model dependences on flushing duration were obtained, which have a downwards trend and well IRC does not depend on increasing flushing duration (Fig. 6).

When washing with a mobile wellbore washing unit it is recommended to replace the cavitator with a spiral type for more thorough cleaning of the filter zone, employing a jet impact on the filter walls. Install a pump with a capacity of not less than 30 m^3/h is required, to create a head level that allows the removal of heavy sand fractions. For the mobile chemical treatment unit, the results of treatment with ammonium bifluoride solutions are shown in Table 3, and the model dependence of RMO efficiency on the treatment duration is shown in Figure 7.

The dependence of IRC on the duration of treatment is not analysable for chemical treatments, because the same volume of decalcifying solutions is fed during different treatment times. Chemical treatment of boreholes using ammonium bifluoride by a mobile chemical treatment unit is one of the most effective and cost-effective methods of RMO in conditions of the RU-6 mine and the Northern and Southern Karamurun deposits.

The introduction of 3 hours of airlift pumping for pumping wells is economically feasible. The specific cost of chemical treatment is significantly lower than that of other RMOs used for the workover of pumping wells. It was determined that the efficiency of stationary chemical treatment increases with the increase of decolorizing solutions supply volume. It is possible to recommend this type of RMO when planning and budgeting well workovers. An increase of sulphuric acid concentration from 20 g/l to 50 g/l for stationary chemical treatment of injection wells does not increase the efficiency of that type of RMO and the cost of the technology increases considerably. To perform RMO of injection wells the best technical and economic parameters have compressor pumping of 1-hour duration and a wellbore pneumatic drilling unit. The determining factor in choosing the optimal complex method was the unit cost. From this point of view, complex chemical treatment with ammonium bifluoride and airlift pumping of wells for 3 hours proved to be

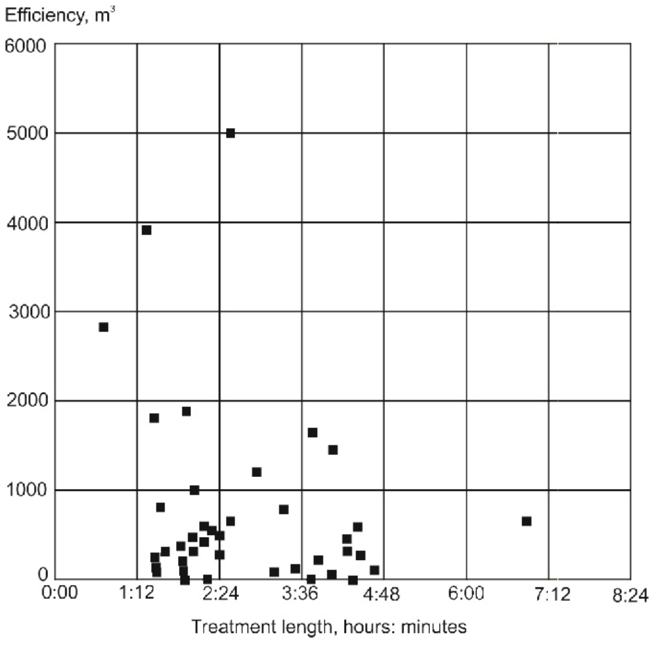


Fig. 6. Model dependence of RMO efficiency on the washing duration (mobile wellbore washing unit)

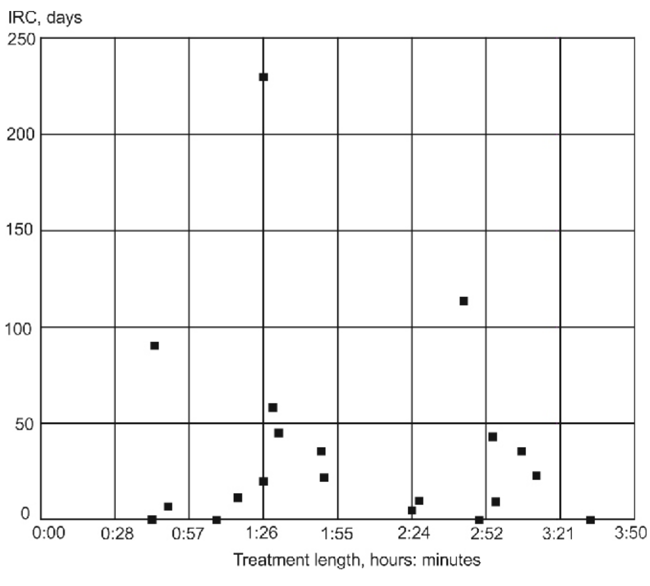


Fig. 7. Model dependence of RMO efficiency on the treatment duration (prospective drilling unit on pumping wells)

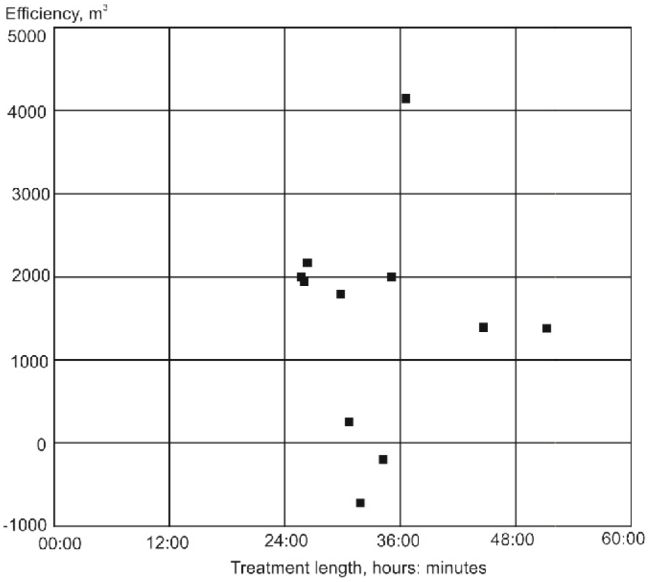


Fig. 8. Model dependence of the RMO efficiency on the treatment duration (BA-15V drilling machine, pumping wells)

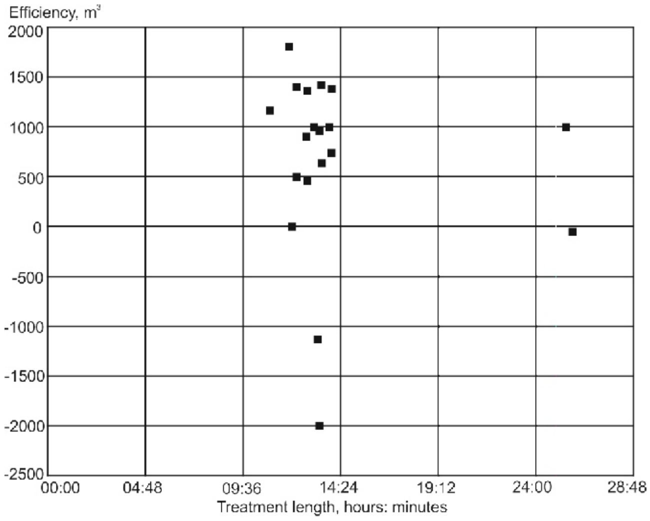


Fig. 9. Model dependence of the RMO efficiency on the treatment duration (BA-15V drilling machine, pumping wells)

the best solution. The influence of RMO duration by drilling machine on the efficiency of the water injection process is shown in Figures 8 and 9.

It is suggested to use volume units such as the amount of solution or liquid volume to measure RMO efficiency. This may be because, in a given context, it is important to know the volume of liquid or solution used, which affects the performance of the process. For example, in the case of mechanical well flushing using a mobile well flushing device, the efficiency can be evaluated based on the volume of fluid used and its impact on cleaning the filter zone. Thus, the volume of fluid used can be a key factor in evaluating the efficiency of the process.

The duration of work for the majority of injection wells is 12–14.5 hours, whereas the process efficiency corresponding to this duration varies considerably and, therefore, these parameters are not related. For injection wells, the dependence of RMO efficiency on treatment duration has a slightly different character. Treatment time varies in the range from 26 hours to 50 hours. The highest efficiency corresponds to a treatment time of about 36 hours, the lowest to 32 hours, and the intermediate to 48 hours. Consequently, for injection wells, the workover time has little, if any, effect on efficiency.

Figures 8 and 9 depict the model dependence of the RMO efficiency on the treatment duration for the BA-15V drilling machine, specifically for pumping wells. In these figures, negative values on the y-axis represent a decrease in efficiency or effectiveness of the RMO process compared to a baseline or reference point. The negative values indicate that as the treatment duration increases beyond a certain point, the efficiency of the RMO process begins to decline. This decline could be due to various factors such as diminishing returns, increased costs, or operational inefficiencies associated with prolonged treatment durations.

When washing with the drilling machine, it is necessary to consider the possibility of replacing the drilling tool with a brush-scrubber used with rotation, water flushing, and running down about 2 m/min, which will probably increase the efficiency of the repair process. Due to high labor costs for regular repair, a drilling machine is not rational to use. Analysis of the dependence of RMO efficiency on treatment duration showed that a pumping duration of around 3–4 hours for pumping wells is the most optimal as regards the ratio of result and time costs (Fig. 10). Also, in comparison with other types, XRVS airlift pumping (capacity) for 3 hours has the lowest cost: 57,950 tenge (128.67 USD).

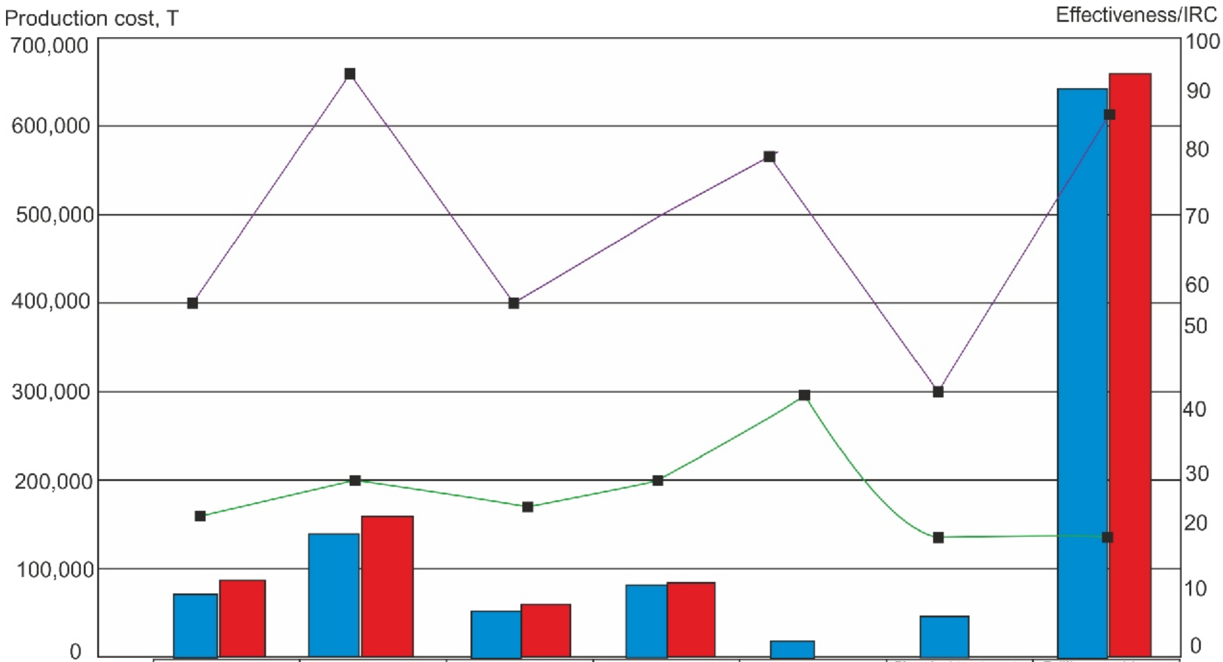
From the point of view of RMO efficiency, we can see that repair of injection wells by methods: XRVS/4 hours; XRVS/1 hour; wellbore pneumatic drilling unit, show the best results (Fig. 11).

No well was effective after carrying out RMO with these methods. The lowest cost of carrying out an airlift pumping (capacity) with a duration of 1 hour is 28.32 in summer and 42.03 in winter, which is much lower than airlift pumping with a duration of 4 hours and the pneumatics. Summing up, we can say that the best technical and economic indices for the repair of injection wells in terms of efficiency/cost/demand ratio are given by two types of pumping. These are compressor pumping with a duration of 1 hour and a wellbore pneumatic drilling unit.

In the treatment group of chemical treatment and airlift pumping of different duration, the best result in terms of efficiency/cost/IRC shows chemical treatment at 20 g/l and airlift pumping (capacity) duration of 3 hours, for which the cost is 74,400 tenge (165.19 USD), and IRC and efficiency are the same with other objects of comparison. In the treatment group of ammonium bifluoride and airlift pumping of different durations, the best result as regards the ratio of efficiency/cost/IRC shows a mobile chemical treatment unit and airlift pumping (capacity) duration of 3 hours, for which the cost is 148,000 tenge (328.60 USD), with the other production indicators the same. Accordingly, the determining factor in choosing the optimal integrated method is the unit cost.

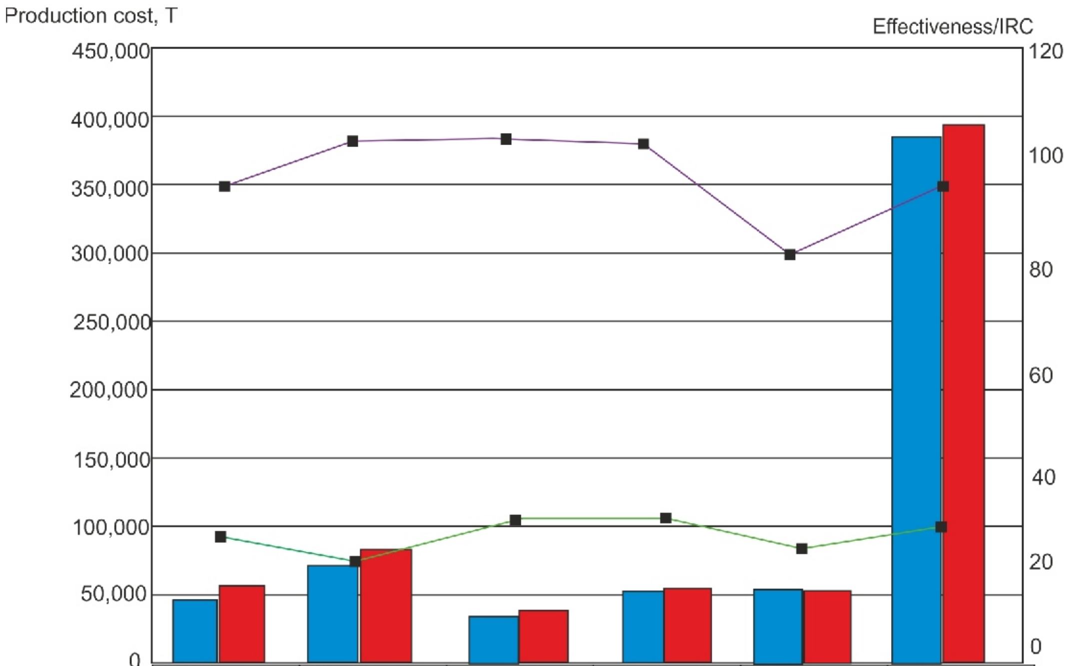
DISCUSSION

Acid leaching is fast and intense, but it contaminates groundwater and leads to sulphate deposits and hence damage to the reservoir. Solid calcium sulphate is deposited in the form of gypsum, calcium sulphate hemihydrate, and anhydrite. Vergnaud (2020) studied the degree of formation of colmatation deposits in process wells during acid leaching. In this research, quantitative assessment of clogging volumes of filters and near-filter zones depending on the type of colmatation was made. Practical recommendations for reducing well clogging during uranium mining were given.



	XRVS (Truck) Pumped/3 hours T	XRVS (Truck) Pumped/8 hours T	XRVS (Tank) Pumped/3 hours T	Mobile chemical treatment unit, pumped, T	Chemical treatment unit, 20 g/l, pumped T	Chemical treatment unit, 50 g/l, pumped T	Drilling machine, pumped, T
Summer	74,836.44	136,056.94	57,950.95	90,084.94	14,490.00	37,894.92	654,211.41
Winter	84,383.56	148,362.18	65,262.32	91,241.94			662,236.56
IRC, days	24	28	24	28	42	22	22
Efficiency	58.3	92.3	58.3	70.0	80.0	45.0	86.0

Fig. 10. Technical and economic RMO values for pumping wells



	XRVS (Truck) Pumped/2 hours T	XRVS (Tank) Pumped/2 hours T	XRVS (Tank) Pumped/1 hours T	Wellbore pneumatic, drilling unit, pumped, T	Mobile wellbore washing unit, pumped, T	Drilling machine, pumped, T
Summer	48,342.84	68,538.39	28,321.82	53,151.12	44,924.61	383,348.32
Winter	55,722.73	84,906.67	42,031.54	53,652.03	46,081.57	388,698.42
IRC, days	24	100.0	29	29	22	27
Efficiency	93.8	22	100.0	100.0	80.0	91.0

Fig. 11. Technical and economic RMO values for pumping wells

Zhou et al. (2020) investigated the recovery of uranium during acid leaching at the Kujiertai deposit and explored the impact of various hydrochemical factors on the dissolution process of uranium oxides. Their findings suggest that altering the acidity or solution volume had minimal effects on the extraction process. Additionally, they observed that classical uranium ore mining techniques involving in-situ borehole leaching with sulphuric acid and hydrogen peroxide solution led to the precipitation of calcium sulphate, resulting in decreased borehole performance.

This research aligns with the findings of other studies that have also noted challenges associated with classical uranium ore mining methods, particularly in terms of borehole performance. However, it is essential to acknowledge potential variations in results due to differences in geological conditions, extraction methods, and experimental setups. Therefore, while Zhou et al. (2020) contributed valuable insights into uranium recovery processes, further research and validation from multiple sources are necessary to establish broader consensus within the scientific community.

Su et al. (2020) conducted laboratory and field tests of uranium leaching using carbon dioxide and oxygen. Their results showed that this approach is feasible in practice. Moreover, such a connection reduces the colmatation of technological wells. Alkaline leaching of ore is less intensive, requires more time, and is less dangerous for nature (Oringojin and Moldabayeva, 2012). The disadvantages include the formation of carbonate salts in the borehole. Neutral leaching technology is used in uranium deposits with a high carbonate content. In comparison with acid and alkaline leaching, this method is the most environmentally friendly technology for ore extraction. Chen et al. (2022) assessed the efficiency of neutral leaching with hydrogen peroxide in a uranium deposit characterized by low uranium content, a significant carbonates content, and pyrite. Their research concluded that neutral leaching with hydrogen peroxide is a viable method for uranium extraction from deposits with high carbonate contents. However, the high proportion of pyrite poses challenges, necessitating the exploration of alternative oxidizing agents.

These findings underscore the importance of considering the specific geological and chemical composition of uranium deposits when selecting extraction methods. While neutral leaching with hydrogen peroxide shows promise in certain geological contexts, the presence of pyrite highlights the need for innovative approaches or alternative chemical agents to optimize the extraction process (Deryaev, 2023b). Further research into alternative oxidizing agents or modifications to existing methods may be necessary to address these challenges effectively and enhance the efficiency of uranium mining operations in similar geological settings.

Enany et al. (2021) carried out optimization of airlift pumping by experimental means due to the absence of exact theoretical equations of water-air flow movement. The authors applied a new system of air injection at different immersion ratios to estimate the capacity of the airlift pump. As a result, the optimal ratio of pipe diameter, air flow rate, and immersion depth in the borehole was determined. It was also found that flow fluctuations reduce pumping efficiency. This can be prevented by proper selection of the volume of injected compressed air and the immersion ratio. The researchers found that the experimental results obtained did not agree with existing theoretical models.

Abed and Ahmed (2022) explored the use of air pulsation to enhance the performance of an airlift pump. By incorporating both theoretical and experimental components, the researchers employed Fourier transform and spectral density functions to analyze the impact of pulsation frequency on pump efficiency across various dip factors. Their experiment involved a comparison between continuous and pulsating air injection methods. The results indicated a significant improvement in pump efficiency by up to 130% when using pulsating air. This finding suggests that air pulsation can be a valuable technique for optimizing airlift pump operation, particularly in deep well applications. By leveraging pulsation frequency as a control parameter, operators can potentially enhance pump performance and productivity, thereby improving overall efficiency in pumping operations conducted at considerable depths (Zakharova et al., 2021).

Underground in-situ leaching significantly contaminates groundwater, but this type of uranium mining does not result in "tailings" and waste in the rock. The potential adverse environmental impacts of underground in-situ leaching are discussed by Woods (2019). The main risk is the leakage of mining or waste solutions outside the process area, which contaminates water resources. This problem can be resolved by controlling the quality of design and construction works. To prevent interstitial contamination, sealing of the outer surface of the process well casing is required. During operation, it is important to minimize the risk of chemicals, industrial wastes, and fuels getting into the aquifer. This can be achieved through preventive maintenance, regular visual inspections, installation of automation systems, and rapid response of personnel in case of emergency (Cheng et al., 2022). When decommissioning a well, it is necessary to control well sealing to prevent interstitial contamination, and restore natural hydraulic gradients of groundwater. Soil remediation is recommended (Dzhalalov et al., 2021), recommend, before starting an ore extraction project, detailed planning of works and risk analysis, and assessment the technical and economic characteristics of the process is needed. It is important to develop measures to restore groundwater properties after the end of the mine operation.

Khan (2020) highlighted the significant environmental impact of depleted uranium as a major source of contamination. Traditional methods of soil restoration, such as coagulation, hydrolysis, and leaching, are often economically unfeasible and impractical for large contaminated areas. In response to this challenge, Khan (2020) proposed an innovative solution involving the use of *Vetiveria citzaniformis* and industrial hemp for phytoremediation.

Phytoremediation, which involves using plants to remove, degrade, or immobilize contaminants in soil, offers a promising alternative for remediating uranium-contaminated sites. Research studies show the potential of these plant species in efficiently absorbing and detoxifying uranium from soil environments. By leveraging the natural abilities of *Vetiveria citzaniformis* and industrial hemp, it becomes possible to restore soil quality and mitigate the harmful effects of uranium contamination in a cost-effective and sustainable manner. Research underscores the importance of exploring nature-based solutions, such as phytoremediation, in addressing environmental challenges posed by uranium contamination. By harnessing the power of plants to remediate contaminated sites, we can not only mitigate environmental risks but also contribute to the long-term restoration and sustainability of ecosystems affected by uranium pollution.

Qi et al. (2019) focused on the application of a bacterial mixture to remediate uranium-contaminated soils. Their study evaluated the efficacy of various bacterial strains in restoring the phytoextraction capacity of certain grass species. Their results indicated that bacterial inoculation could effectively restore damaged soil by converting soluble uranium salts into insoluble, non-toxic forms. This finding underscored the potential of microbial remediation strategies in mitigating uranium contamination in soil environments. By harnessing the metabolic activities of specific bacteria, it becomes possible to transform harmful contaminants into less hazardous compounds, thus facilitating the restoration of soil health and ecological balance. The study highlighted the promising role of bacterial-mediated processes in addressing environmental challenges associated with uranium contamination and underscored the importance of further research in this field.

Lakaniemi et al. (2019) studied the ability of bacteria to bioreduce uranium. Their research explained in detail the processes that lead to the purification of uranium-contaminated space and described the factors that influence the kinetics of recovery of the hydrogen index and the chemical composition of water. Banala et al. (2021) compared the interaction of different groups of microorganisms with uranium. The researchers described the mechanism of uranium sorption, mineralization, reduction, and accumulation by different groups of bacteria, and carried out a comparative evaluation of biological and chemical means to neutralize the toxic effect of uranium ore.

Sarkar (2019) considered the trend of nuclear power development in the world. Despite the high demand for energy reproduced in nuclear power plants, this industry creates difficulties in health care. The reasons for active uranium mining in African and Asian countries are explained. It was emphasized that noncompliance with labour standards in uranium mining has resulted in lower operating costs. Evidence was given of environmental violations and pollution, which pose a significant threat to public health. Recommendations for environmental control and public health oversight were presented.

While such research provides valuable insights into the optimization of workover operations in uranium mines, it overlooks an important aspect - the environmental impact. Many contemporary studies fail to address the necessity of conducting RMO in technological wells of uranium mines and do not explore the processes of colmatation and methods to mitigate them. Although the proposed methods of RMO are justified in terms of technical and economic feasibility, the environmental implications remain unexplored, and practical recommendations to minimize environmental damage are lacking. Therefore, future research should aim to integrate environmental considerations into the optimization of workover operations, ensuring sustainable practices in uranium mining.

CONCLUSIONS

Theoretical features of uranium mining regarding the causes of colmatation in the filters and near-filter zones are described, and the necessity of carrying out water shut-off and using existing technologies to improve the productivity of technological wells are substantiated. A comparative analysis of technical and economic indicators of water shut-off at the deposits of “North and South Karamurun” was carried out, and the most effective means and alternative modes of implementation were proposed.

Performance degradation occurs as a result of the accumulation of colmatation deposits on filters and near-filter zones, stemming from underground well leaching. This process encompasses various phenomena, with mechanical and chemical colmatation being particularly relevant to this study. Chemical colmatation disrupts filtration flow characteristics, while mechanical colmatation is attributed to suffusion processes and the entry of contaminant particles into the filter. Remedial measures to address colmatation and restore well performance typically involve mechanical, chemical, and well development interventions. The use of self-propelled drilling rigs is reasonably effective and economical but requires a long time to carry out, 2 days or more. Treatment with reagent solutions successfully removes colmatated deposits. Nevertheless, the use of this method is not environmentally safe. Pneumatic pulse treatment destroys sediments on the filter with the help of compressed air energy. It is an environmentally safe method; however, it is ineffective for technological wells with a low static level of formation water and low permeability. Airlift pumping by a compressor is one of the most economical methods. A significant disadvantage is that this technology has a low efficiency, it is not recommended for use in wells at great depths. When planning the work, it is important to consider the duration of pumping for a particular type of well.

Comparative analysis of repair and maintenance operations costs, as well as indicators of inter-repair cycle and efficiency, shows the economic feasibility of implementation of 3-hour (capacity) airlift pumping for pumping wells. An increase in sulphuric acid concentration from 20 to 50 g/l for stationary chemical treatment of injection wells did not increase the efficiency of this type of repair and maintenance operation. At the same time, the cost of one chemical treatment of the wells increased from 14,500 tenge to almost 38,000 tenge. For the repair of injection wells on the efficiency/cost/inter-repair cycle ratio. the best technical and economic indicators have a compressor pumping duration of 1 hour (capacity) and a wellbore pneumatic drilling unit.

The determining factor in choosing the optimal complex method was the unit cost. For the group of methods that combine chemical treatment of wells and airlift pumping, the most optimal method from this point of view was a chemical treatment of 20 g/l and airlift pumping (capacity) of 3 hours, for which the cost price is 74,400 tenge.

To improve uranium production efficiency and ensure stable operation of process wells in the future, it is recommended to conduct research on new methods and technologies to effectively manage well colmatation and increase productivity. Mechanical, chemical and well development methods should be implemented to effectively remove colmatation deposits. It is important to study the impact of various factors, such as the concentration of sulfuric acid solution and the duration of the remediation processes, on the effectiveness of well workovers and maintenance operations.

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