Mining of Mineral Deposits
Volume 19 (2025), Issue 1, 132-141

MMD JOURNAL / MINING.IN.UA

https://doi.org/10.33271/mining19.01.132

Research of influence of various factors on repair-and-renewal operations in technological wells during uranium geotechnology in complex mining and geological conditions

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Abstract

Purpose. The research aims to improve the efficiency and reliability of repair-and-renewal operations in technological wells in complex mining and geological conditions involved in in-situ uranium leaching by identifying and analyzing the influence of geological, geochemical and technical factors.

Methods. The research is based on a comprehensive analysis of field data on well designs, rock characteristics and geochemical conditions of ore-bearing horizons. Filtration parameters, types of stripped rocks, composition of working solutions and peculiarities of well operation with different operating durations are analyzed. Statistical analysis methods, including correlation and regression analysis, are used to systematize the factors influencing the frequency and efficiency of repair activities. The results are compared with laboratory experiments that assess the effectiveness of various chemical reagents taking into account mineralogical-geochemical peculiarities of uranium ores.

Findings. The conducted analysis makes it possible to determine that the intensity of repair-and-renewal operations is directly dependent on a combination of several factors, among which the most important are the geological structure of ore-bearing rocks and hydrochemical conditions of ore. It has been shown that with increased reservoir productivity, the need for frequent repair-and-renewal operations increases, which is explained by more active operating mode and, consequently, an increased load on operational elements. Characteristic patterns of changes in filtration coefficient and chemical composition of solutions in filter intervals have been revealed, allowing for more accurate prediction of the time and volume of the necessary repairs.

Originality. Dependences of the quantity of repair-and-renewal operations of wells on reservoir productivity and geochemical conditions of ore at different stages of in-situ uranium leaching through boreholes have been obtained.

Practical implications. The results obtained enable engineers and technologists to develop more reliable and flexible well maintenance and repair plans tailored to specific geologic-hydrodynamic and geochemical conditions. It reduces the risks of accidents, but also increases the overall uranium production level through more efficient use of equipment and working reagents.

Keywords: *uranium leaching, mining productivity, repair-and-renewal operations, geological conditions, ore-bearing rocks, technological blocks*

1. Introduction

In the modern world, uranium mining is a strategically important industry, as nuclear power continues to play a significant role in ensuring global energy security [1]-[3]. According to the International Atomic Energy Agency (IAEA), uranium accounts for a significant portion of the fuel supply for nuclear power plants, and many countries are striving to develop cleaner, more efficient and safer uranium mining technologies [4].

Therefore, particular attention is paid to improving underground leaching methods (in-situ leaching, ISL), which minimizes environmental impact and significantly reduces capital expenditure compared to traditional open-pit and mine mining methods [5]-[7]. A recent systematic review by Kunarbekova et al. [8] highlights current trends and future development prospects of the mining and metallurgical industry in Kazakhstan, including advancements relevant to uranium extraction.

Received: 7 October 2024. Accepted: 10 March 2025. Available online: 30 March 2025

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

One of the key components of successful uranium mining using the in-situ leaching method is to ensure uninterrupted operation of technological wells. These wells play a dual role, serving, on the one hand, to supply leaching solution (injection wells) and, on the other hand, to withdraw uranium-rich pregnant solution (extraction wells) [9], [10]. Since the mining process is highly dependent on efficient solution circulation, repair-and-renewal operations (RRO) in technological wells becomes crucial in maintaining stable production, while reducing the risk of accidents. In the event of a well failure, the cost of repairing the wells, and even more so of replacing them (by drilling new wells), can be significant, which will have a negative impact on the economic performance of the mining enterprise [11]-[14].

The authors [15]-[17]emphasize that the improvement of the efficiency of repair-and-renewal activities is largely determined by timely and accurate diagnosis of the technical condition of technological wells. In the above studies, a comprehensive approach is proposed, including the use of sensor monitoring systems, allowing real-time information to be obtained on the dynamics of changes in the operating parameters (pressure, flow rate, chemical composition of the sampled solution, etc.). Sensor data are processed in integrated systems, enabling rapid detection of adverse processes, such as colmatation, corrosion, leakage, and take corrective actions. Similar conclusions have been reached by foreign researchers working on the systems of smart wells in the oil-gas industry, where the issue of the reliability of casing pipes and operational control of wellbore condition is also of paramount importance [18], [19]. This experience, transferred to the uranium mining sector, confirms that timely and accurate diagnostics cannot only reduce financial losses, but also increase the level of industrial and environmental safety [20]-[23].

At the same time, according to [24]-[26] data, the right choice of materials and repair technologies remains an equally important factor influencing the durability and reliability of technological wells. In uranium mining environments, where aggressive acidic or alkaline reagents are commonly used, conventional metals can corrode rapidly. In recent years, there has been extensive research into the development and implementation of polymer coatings and composite materials that provide increased resistance to aggressive chemical environments and mechanical wear. Successful experiments in the field of using new types of cement slurries, as well as high-strength composites for sealing joints between pipe strings, have made it possible to increase the service life of equipped wells. According to the data in [27], innovative materials based on heat-resistant polymers have shown a significant reduction in the corrosion coefficient and an increase in the overall non-repair service life.

Against the background of the mentioned achievements, an important place is occupied by the improvement of methods of drilling and cementing of casing pipe strings, since the quality of initial wellbore preparation largely determines its further operation. The use of specialized drilling fluids with optimal rheological properties that can significantly increase the rate of drilling and improve the wellbore quality is demonstrated in [28]. In parallel, new tamping methods using microfoam concrete and chemically resistant additives can more effectively prevent leaks and reduce the risk of production interval colmatation.

Despite the existence of a significant body of research aimed at improving the efficiency of repair-and-renewal operations in the uranium-mining sector, several important issues remain insufficiently studied. In particular, there are no systematic studies on a comprehensive analysis of the influence of geological and geochemical factors (mineral-petrographic composition of ore-bearing rocks, their permeability, hydrochemistry of productive horizons) on the results of RROs. In addition, the issue of the optimal ratio of injection and extraction wells in in-situ leaching blocks, which can significantly affect the hydrodynamics of the reservoir and, consequently, the efficiency of repair measures, has not yet been properly highlighted. Finally, the literature hardly considers the aspect of quantitative influence of frequency and volume of repair-and-renewal operations on reservoir productivity – most of the studies are limited to describing technologies and materials without in-depth economic-technological analysis.

In order to fill this gap, the present research examines in detail one of Kazakhstan's uranium facilities, the Mynkuduk field. Kazakhstan remains the world leader in uranium mining in recent years, with a significant portion of resources being developed using in-situ leaching method [4], [29]. The Mynkuduk field, located in South Kazakhstan Oblast (some sources point to Kyzylorda Oblast bordering South Kazakhstan), is one of the largest and most promising in terms of uranium ore reserves. The Central site in this field is characterized by relatively complex mining and geological conditions as well as difficult hydrogeological conditions, with technological blocks operating here for several years [30]. In order to maintain high production performance and prevent emergency situations at this site, regular repair-and-renewal operations are performed to replace and repair filters, seal shafts, reconstruct the annular space, etc. However, there remain unresolved issues of optimizing these processes, taking into account geochemical peculiarities, changes in rock properties as the resource is exhausted [31], as well as the influence of accumulated sediments and chemical compounds on pipe walls [32].

The practical significance of the research conducted at Mynkuduk field is conditioned not only by economic benefits and the need to ensure stable production volumes, but also by the increased requirements for industrial and environmental safety in the context of intensified mining operations. Studying the patterns of change in the state of technological wells and elaboration of recommendations for improving the RRO can be adapted to other uranium fields in the world with similar geological-hydrodynamic conditions. The results obtained at Central site may serve as a basis for further implementation of modern technologies within the framework of the smart uranium-mining concept, actively developed by a number of leading international scientific groups [33], [34].

Thus, the present research aims to identify and analyze those factors that form a combined influence on the performance and intensity of repair-and-renewal activities. These factors, in addition to the characteristics of materials and diagnostic methods already studied in a number of foreign studies, include:

– geological peculiarities of ore-bearing rocks (physical-mechanical properties, granulometric composition, degree of homogeneity and stratification);

– geochemical characteristics of the reservoir (mineralogical composition, chemical reactions of leaching solutions, formation of sediments and secondary minerals);

– technical parameters of wells (wellbore design and diameter, filter types and sizes, casing string peculiarities, cementing methods);

– hydrogeological conditions (permeability, filtration coefficient, interaction mode of injection and extraction wells);

– frequency and volume of RROs conducted, as well as their correlation with mining productivity.

Despite numerous studies [15]-[17], [24]-[27], it is the cumulative consideration of these factors with subsequent quantitative analysis of their influence on the success of RROs in the conditions of a particular site (in this case, the Central site of the Mynkuduk field) remains an urgent scientific-practical task.

The purpose of this paper is to determine the influence of geological, geochemical and technical factors on the efficiency of well repair-and-renewal processes at Central site of the Mynkuduk field. To achieve this purpose, an extensive analysis of operational monitoring data, results of geological-hydrodynamic studies, as well as many years of experience in conducting RROs at this site have been conducted. The results obtained may contribute to further improvement of in-situ uranium leaching methods, ensuring the more reliable operation of technological blocks and reducing the risks of emergency production stoppages.

Structurally, the paper includes a problem setting and literature review (this section), the methodological part, which reveals the details of the conducted research (analytical and experimental methods, statistical tools used, etc.), as well as the results of the analysis and discussion of conclusions, supported by schemes and tables. It will conclude with recommendations for the practical application of the results obtained and the direction of further research.

Thus, taking into account the above-mentioned trends and knowledge gaps, it can be argued that the study and systematization of factors influencing repair-and-renewal operations in conditions of in-situ uranium leaching is a demanded direction. The experience gained at the Mynkuduk field can play an important role in improving the efficiency of uranium mining not only in Kazakhstan, but also in other countries oriented towards safe and technological development of nuclear power.

2. Research methods

The research is conducted using an integrated approach, which includes several stages and methods. The initial stage is a thorough collection of data on technical characteristics of wells, which includes studying their design, filter sizes, and information on the geological and hydrogeological parameters of the field. This includes analyzing the rock granulometric composition, geochemical composition and physical-chemical properties of the pregnant solutions. The data obtained are thoroughly processed, generalized and structured according to the different technological blocks into which the Central site of the Mynkuduk uranium field is divided.

The data collection stage is followed by an analysis aimed at identifying relationships between well technical parameters, field geology and the efficiency of repair-and-renewal operations. This analysis includes assessing the impact of parameters such as well design, filter size, and geological factors on the performance of the operations conducted. It helps identify the key parameters that have the greatest impact on well performance and the efficiency of repair-and-renewal activities.

Systematization of geological and geochemical data is important for understanding the field's characteristics. A detailed analysis, including rock types, chemical composition, and physical-chemical properties of pregnant solutions, helps evaluate the influence of these parameters on the efficiency of repair-and-renewal operations [35]-[39]. A list of wells is then compiled, taking into account their geologic and geochemical environment. For each well, the quantity of RROs performed is determined. Then, the data are aggregated and presented in summary tables and graphs to provide a visual comparison of RRO efficiency under different geochemical conditions [40].

To analyze the impact of different methods of assessing the efficiency of repair-and-renewal operations, data were collected on various methods for assessing the efficiency of RRO used in LLP Mining Company "ORTALYK".

The Central Mynkuduk mine uses a variety of repair-and-renewal methods designed to maintain technological wells. These methods include:

– pneumatic impulse treatment of wells using the "Hydroimpulse" unit (PIT);

– airlift well pumping (AP);

– hydro-swabbing of wells (HS);

– complex-1, including pneumatic impulse treatment with purification (blowdown) and airlift pumping of technological wells (K-1);

– complex-1 with additional chemical treatment with ammonium bifluoride (K-1 + ChT);

– hydrodynamic treatment of wells followed by chemical treatment with ammonium bifluoride (HDT + ChT);

– hydro-swabbing of wells using chemical treatment with ammonium bifluoride (HS + ChT).

Data on the quantity of RROs conducted and their efficiency for the period 2021-2023 are also analyzed. This makes it possible to identify the dynamics of changes in the efficiency of the work performed and to compare the results with the methods used to assess efficiency. Based on the collected data, graphs are plotted showing the dependence of RRO conducted efficiency on various parameters, such as the productivity of wells before conducting RRO and their injection capacity. This makes it possible to see the influence of these parameters on the efficiency of the work performed and to assess the conformity of the used assessment methods with the actual results.

A correlation analysis is then performed to identify the dependence between the quantity of RROs and geotechnological parameters of ores and ore-bearing rocks at the Central site of the Mynkuduk uranium field. The parameters considered are the quantity of RROs in the wells, the production rate of mineralization in the filter zone, the length of the filters, the thickness of the 3rd and 4th lithotypes in the filter zone, as well as the filtration coefficients (K_f) of the 3rd and 4th lithotypes in the filter zone.

When analyzing the RRO efficiency factor, data were collected for the period from 2021 to 2023.

For more in-depth analysis, the change in the uranium content in the pregnant solution over time and the values of efficiency factors are also studied.

3. Results and discussion

Pairwise correlation coefficients are calculated to analyze the relationship between the quantity of RROs and technological characteristics of rocks. These coefficients are calculated both for individual extraction and injection wells, as well as for all wells as a whole. In addition, the analysis is conducted both annually and for the entire period from 2021 to 2023. The results obtained for block No. 10-51 are given in more detail in Table 1.

The positive relationship between RRO and the length of injection well filters can be explained by the fact that as the length of filters increases, the probability of their clogging and filling of the near-filter zone with various colmatation products, both chemical and mechanical nature, increases. This, in turn, leads to reduced well productivity and an increased need for repair-and-renewal operations.

Based on the data of the 3rd lithotype filter zone thickness, ranging from 20 to 100% of the total filter length, and the lack of a noticeable correlation between the quantity of conducted repair-and-renewal operations and the 3rd lithotype filtration coefficient in the zone of extraction well filters, it can be assumed that there is a negative trend in conduct of RROs with an increase in the 3rd lithotype thickness in extraction wells. This may be due to the fact that an increase in the 3rd lithotype thickness may lead to changes in geological well structure, which in turn may reduce the efficiency of conducting RRO in these wells. At the same time, the data of the table show that there is a positive correlation between the performance of repair-and-renewal operations, well productivity and injection well filter length. This is also demonstrated by the correlation graph in Figure 1.

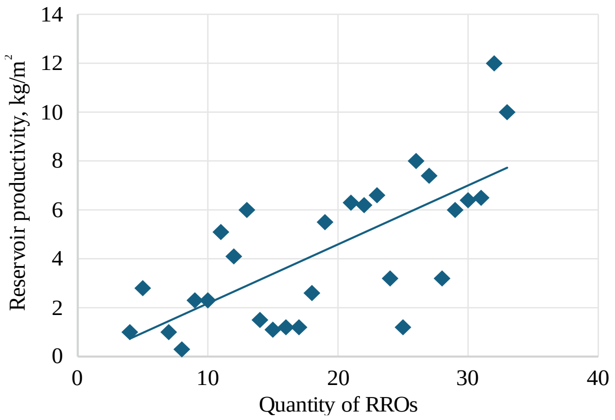

Figure 1. Dependency graph of the quantity of RROs on reservoir productivity of technological block No. 10-51

Summarized total data on pairwise correlation coefficients for 2021-2023 are presented in Table 2.

Table 1. Pairwise correlation coefficients between the quantity of RROs and geotechnological parameters of technological wells of block No. 10-51

RRO quantity by years	Productivity, kg/m²	Filter length, m	K_f in the filter zone of the 3rd and 4th lithotypes, m	Thickness of the 3rd and 4th lithotypes, m	K_f of the 3rd lithotype filter zone, m/day	Thickness of the 3rd lithotype filter zone, m
Extraction wells						
RRO qty. in 2021	0.14	0.54	0.47	0.01	0.59	-0.44
RRO qty. in 2022	-0.15	0.18	0.61	-0.14	0.17	-0.55
RRO qty. in 2023	-0.33	0.30	0.56	0.14	0.22	-0.56
Total RRO	-0.19	0.28	0.65	-0.05	0.25	-0.60
Injection wells						
RRO qty. in 2021	0.60	0.60	-0.39	0.50	0.10	0.11
RRO qty. in 2022	0.67	0.62	-0.07	0.28	-0.10	-0.20
RRO qty. in 2023	0.59	0.56	-0.02	0.06	0.04	-0.11
Total RRO	0.71	0.67	-0.11	0.27	-0.02	-0.14
All the wells						
RRO qty. in 2021	0.45	0.59	0.05	0.35	0.22	-0.15
RRO qty. in 2022	0.31	0.32	0.28	0.06	0.01	-0.32
RRO qty. in 2023	0.27	0.40	0.24	0.08	0.10	-0.28
Total RRO	0.36	0.43	0.27	0.11	0.07	-0.32

From the performed analysis of the available data, it follows that the positive correlation between the conduct of repair-and-renewal operations and some technological parameters confirms the hypothesis that with an increase in the values of these parameters, the RRO quantity increases. A positive trend is noted in the cases of productivity – 7 times, filter length – 4 times, thickness of the 3rd and 4th lithotypes – 5 times. A negative correlation is also observed between RROs and some technological parameters, which corresponds to hypothesis that as the parameter values decrease, the RRO quantity increases. Negative trend is observed in cases with K_f in filter zone of the 3rd and 4th lithotypes – 1 time, thickness of the 3rd and 4th lithotypes – 1 time.

A positive correlation is between RROs and some technological parameters, which does not confirm the hypothesis under consideration. This is noted in the cases with K_f in the filter zone of the 3rd and 4th lithotypes – 6 times.

The correlation analysis between the quantity of RROs conducted in technological wells and geotechnological parameters of ores and ore-bearing rocks shows multidirectional and generally insufficiently convincing results. Although both positive and negative trends were expected to be found, most of the analysis is uninformative because the correlation coefficients are very low.

It was expected that high correlation coefficient values would indicate a linear dependence between the quantity of RROs and geotechnological parameters of the medium. In reality, such a dependence has proved to be practically impossible, given the many objective and subjective factors influencing the quantity of RROs conducted.

Table 2. Summarized total data on pairwise correlation coefficients for 2021-2023 for technological blocks of the Central site of the Mynkuduk field

Technological block No.	Well type	Productivity, kg/m^2	Filter length, m	K_f in the filter zone of the 3rd and 4th lithotypes, m	Thickness of the 3rd and 4th lithotypes, m
In-situ leaching area	Extraction	-0.49	-0.12	-0.64	0.05
	Injection	0.14	0.00	0.38	-0.35
	All the wells	0.03	0.01	0.28	-0.22
63-4	Extraction	0.54	-0.01	0.40	-0.50
	Injection	0.32	0.09	-0.01	1.00
	All the wells	0.34	0.07	0.18	-0.18
68-1	Extraction	0.54	-0.47	0.09	-0.02
	Injection	0.27	0.08	0.15	-0.14
	All the wells	0.28	0.02	0.03	0.00
68-2	Extraction	0.74	0.34	0.14	-0.18
	Injection	0.16	0.29	0.26	-0.19
	All the wells	0.11	0.21	0.28	-0.05
69-1	Extraction	-0.12	-0.05	-0.06	0.35
	Injection	0.30	0.19	0.06	0.42
	All the wells	0.15	0.08	-0.08	0.42
69-2	Extraction	0.40	-0.10	0.13	-0.13
	Injection	0.03	0.03	-0.19	0.23
	All the wells	0.15	0.04	-0.09	0.38

Nevertheless, the analysis shows a positive trend between the quantity of RROs and productivity in extraction and injection wells. This result is logical: where there is more ore, it is necessary to maintain high productivity of the technological wells, which requires more RROs.

The impact of geochemical rock types on the need to conduct RROs is further studied. Two main geochemical rock types have been identified in the Central site of the Mynkuduk field: grey-colored diagenetically recovered sediments and epigenetically reservoir-oxidized red-colored rocks.

In order to assess the influence of geochemical conditions on the quantity of RROs conducted, statistical data were collected on the quantity of RROs of wells in non-oxidized and oxidized rocks of different technological blocks.

This will allow the expected quantity of repair-and-renewal operations to be predicted when new blocks are put into operation, depending on the geochemical conditions of the wells (Fig. 2).

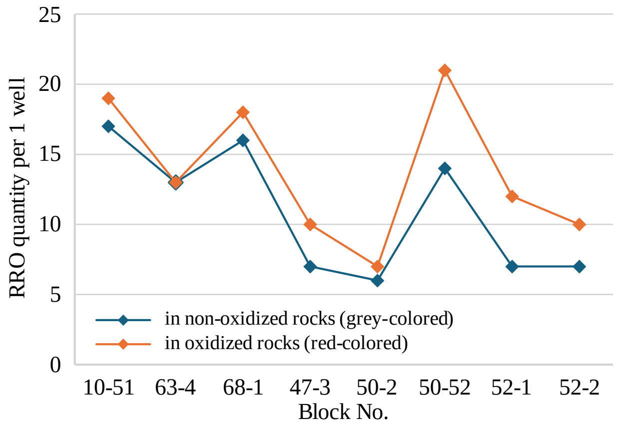

Figure 2. Comparison of RRO quantity per 1 well in non-oxidized and oxidized rocks

The analysis shows that the quantity of RROs in wells located in the reservoir oxidation zone (ROZ) should exceed the quantity in wells located in non-oxidized (grey-colored) rocks by 20%.

Field mining experience shows that the ratio between injection and extraction wells significantly influences the efficiency of operation and the quantity of RROs conducted. The higher the share of injection wells compared to extraction wells, the more intensive is the field mining.

Increase in the quantity of injection wells allows optimizing their injection capacity while maintaining the required flow rate in extraction wells. This reduces the load on injection wells and reduces the quantity of work required to repair and renew them. For example, at the Central Mynkuduk in-situ leaching mine, the implementation of new standards, which reduced the extraction well flow rate from 10 to 6 m^3/hour, has led to a reduction in the load on injection wells and, consequently, to a reduction in the quantity of RROs.

Thus, the ratio between injection and extraction wells plays a key role in efficient mining of technological blocks. The optimal value of this ratio is at least 3-4 injection wells per 1 extraction well. Maintaining this balance not only reduces the quantity of repair operations, but also reduces the acidification stage duration, which accelerates the overall mining of technological blocks.

Putting new technological blocks into operation leads to increased load on injection wells of adjacent blocks. This is due to the need to supply large volumes of hydrogen-sulfide water (HSW) to ensure a balance with the extraction wells of all adjacent blocks. Such an increase in load leads to an increase in the quantity of RROs in the injection wells in order to provide the required injection capacity of the wells. This can be clearly seen in the example of technological block No. 10-51 (Fig. 3). Table 3 presents data on the efficiency of the types of RROs for May 2023.

It should be noted, however, that this efficiency calculation methodology has the disadvantage in that the sample set includes wells with different operating periods, which may lead to more consistent results for certain types of RROs.

The graphs in Figures 3-6 demonstrate the dependence of the efficiency of RROs conducted by LLP Mining Company "ORTALYK" on the productivity of wells before conducting RROs. To plot the graphs of RRO efficiency, sample sets are formed for groups of wells with different flow rates and injection capacities before conducting RRO.

Table 3. Efficiency of the RRO types for May 2023

RRO type	Well	Quantity	Flow rate/ injection capacity, m^3/hour				Efficiency, %
			before	after	increase	standard	
PIT	Injection	117	1.5	3.00	1.50	2.7	111.11
HS	Extraction	13	3.5	7.90	4.40	7.9	100.00
HDT	Extraction	13	4.1	8.10	4.00	6.2	130.65
AP	Inj.+ Extr.	68	3.4	5.00	1.60	5.9	84.75
HS + Ch/T	Extraction	17	3.7	8.30	4.60	6.3	131.75
HDT + Ch/T	Extraction	17	3.9	8.80	4.90	6.2	141.94
Ch/O	Extraction	6	3.5	9.10	5.60	6.2	146.77
K-1	Injection	107	0.9	2.10	1.20	2.2	95.45

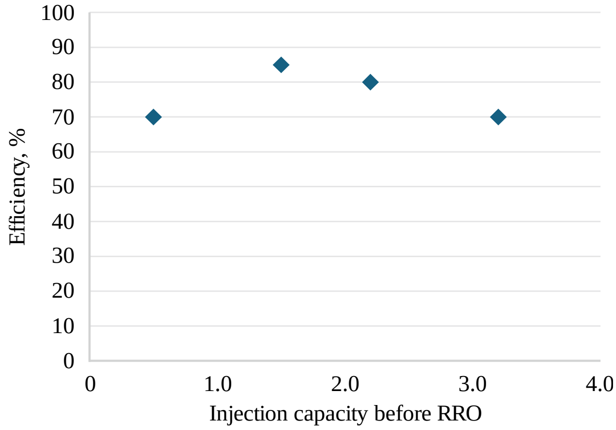

Figure 3. Dependence of the efficiency of airlift pumping in injection wells on injection capacity of wells before RRO

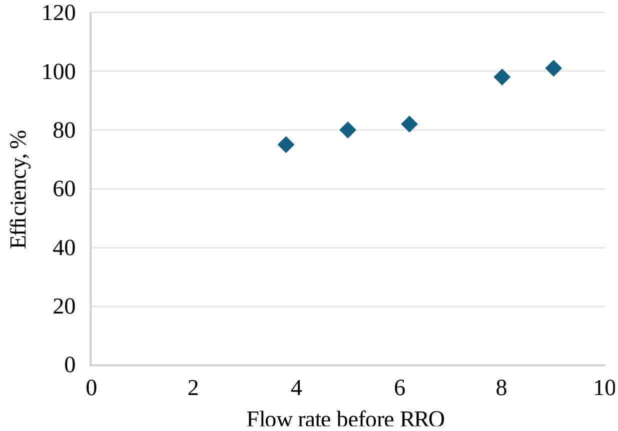

Figure 6. Dependence of the efficiency of hydro-swabbing in extraction wells on injection capacity of wells before RRO

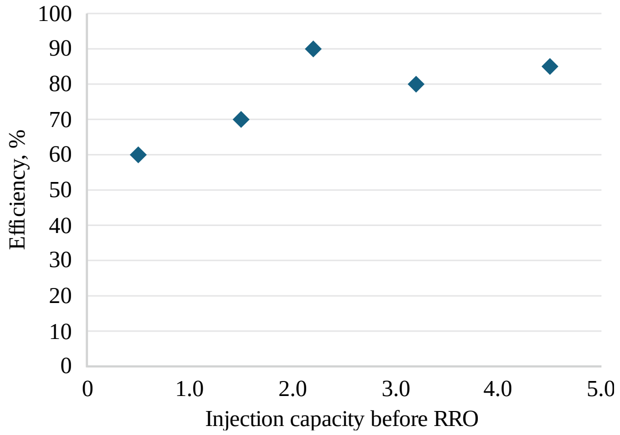

Figure 4. Dependence of the efficiency of pneumatic impulse treatment of injection wells on injection capacity of wells before RRO

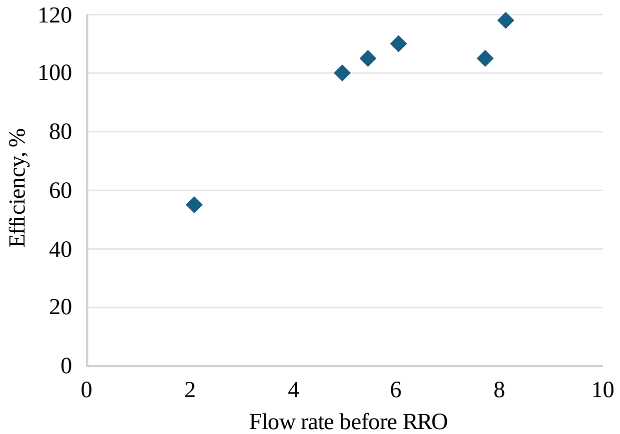

Figure 5. Dependence of the efficiency of hydrodynamic treatment of extraction wells on injection capacity of wells before RRO

From the analysis of graphs, it follows that the efficiency of conducting production flushing in injection wells is achieved at injection capacity before RRO about 1.5 m^3/hour. At the same time, flushing with reverse flow is effective in injection wells if the injection capacity exceeds 2.0 m^3/hour. For hydrodynamic pressuring up in extraction wells, efficiency is shown before RRO at flow rate of more than 4.0 m^3/hour. When hydrostatic pressuring up is applied to extraction wells, the efficiency increases in proportion to the flow rate before conducting RRO. Thus, the efficiency of RRO, according to LLP Mining Company "ORTALYK" assessment system, depends on the initial flow rate and injection capacity of wells before conducting RRO.

Sometimes the analysis of RRO efficiency includes an assessment of the inter-repair cycle (IRC) as a criterion for success. However, it is important to consider that the IRC only makes sense if the specified reduction standards of flow rate or injection capacity are strictly adhered to. In practice, the IRC is determined by geotechnical factors influencing the change in well productivity after conducting RRO.

By processing the data on the quantity of RROs in injection wells (Fig. 7) and extraction wells (Fig. 8) for the period from 2021 to 2023, the dependences of the efficiency of RROs on the quantity of wells have been obtained.

The graphs presented show that the highest quantity of wells were treated in 2022. However, the extraction wells had average efficiency above 100%, which may indicate the effective use of the method. At the same time, the average efficiency of pneumatic impulse treatment of injection wells from 2021 to 2022 was below 80%, and only exceeded 100% in 2023. This is probably due to a decrease in the quantity of repaired wells and the transition to a new regulation of extraction well productivity, which reduced the flow rate from 10.0 to 6.0-8.0 m^3/hour.

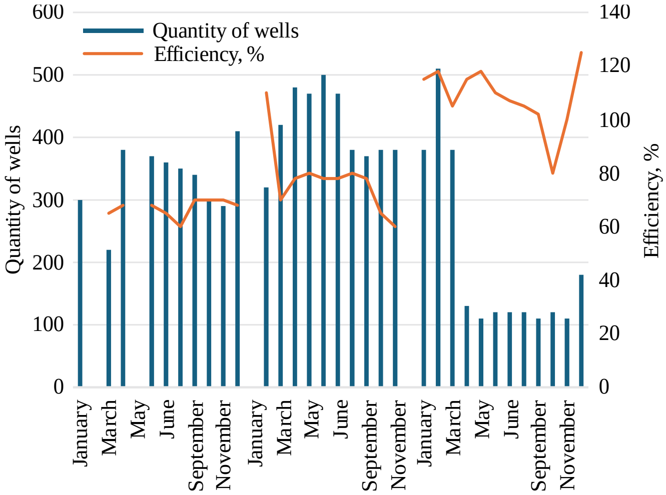

Figure 7. Graphs of efficiency and quantity of RROs in injection wells

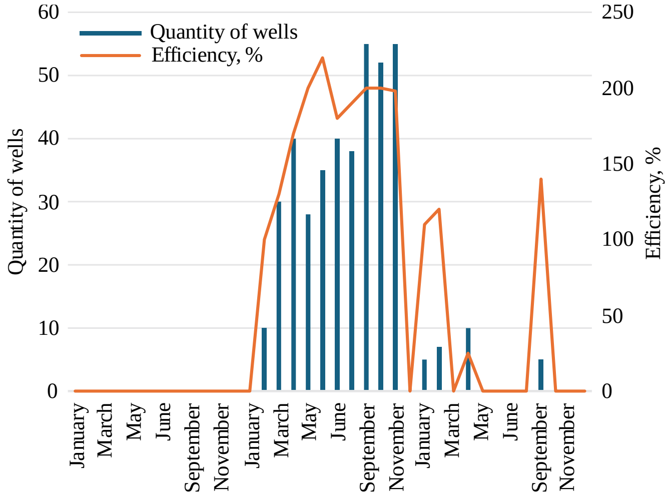

Figure 8. Graphs of efficiency and quantity of RROs in extraction wells

In general, injection wells integrated into operation with three extraction wells require more RROs than wells connected to one or two extraction wells. Therefore, when new adjacent blocks are put into operation, an increased need for RROs can be expected to occur in injection wells that were originally peripheral and operated with only one or two extraction wells.

Analyzing the operation of blocks at different stages of ISL through boreholes, it becomes evident that the quantity and types of necessary repair-and-renewal operations, as well as material-resource costs of the inter-repair cycle are different. Table 4 shows that the bulk of RROs is concentrated at the active leaching stage, when uranium-rich pregnant solutions begin to inflow.

Table 4. Summary table of characteristics of repair-and-renewal operations for cells of technological block No. 10-51 at different stages of ISL through boreholes

ISL stage		Cell no.	Average IRC		Total RRO		% RRO	
			extraction	injection	extraction	injection	extraction	injection
Advanced acidification stage		10-51-01	51	57	3	19	15.8	17.6
		10-51-02	59	43	3	27	37.5	27.6
		10-51-06	76	56	3	23	10.3	21.7
		10-51-08	67	74	2	11	6	20
		10-51-010	34	48	5	29	28	23
		For cell	57	56	16	109	15	22
Active leaching stage	Passage of peak uranium contents	10-51-01	52	37	8	44	42.1	40.7
		10-51-02	49	51	3	48	37.5	49.0
		10-51-06	16	39	11	42	37.9	39.6
		10-51-08	22	90	21	19	66	35
		10-51-010	32	36	8	42	44	34
		For cell	34	51	51	195	48	40
	Uranium content plateau at the level of 100 mg/dm^3	10-51-01	60	61	6	26	31.6	24.1
		10-51-02	208	85	1	16	12.5	16.3
		10-51-06	26	48	5	18	17.2	17.0
		10-51-08	69	116	2	16	6	30
		10-51-010	76	59	4	32	22	26
		For cell	88	74	18	108	17	22
	Transition to an extraction well productivity of 8-6 m^3/hour	10-51-01	114	49	2	19	10.5	17.6
		10-51-02	no data	37	1	7	12.5	7.1
		10-51-06	22	75	10	23	34.5	21.7
		10-51-08	45	48	7	8	22	15
		10-51-010	no data	43	1	22	6	18
		For cell	60	50	21	79	20	16

It is clear from the data provided that the volume of repair-and-renewal operations, as well as their IRCs are directly dependent on the stage of the in-situ uranium leaching process:

1. The quantity of RROs increases significantly when uranium-rich pregnant solutions approach the extraction well, accounting for almost half of the total quantity of RROs during the study period.

2. IRC for the same type of RRO varies depending on the stage of the in-situ uranium leaching process.

3. Assessment of the efficiency of standard RRO types is necessary, given the specific stage of the in-situ leaching process.

The results of this research, conducted at the Central Mynkuduk in-situ leaching mine, in contrast to previous studies, emphasize many factors influencing the operation of technological wells, including geologic peculiarities. It has also been revealed that the efficiency of the work performed depends on the stage of the uranium leaching process and can vary greatly depending on the time of well operation and operating conditions.

This research has also identified a variety of factors that need to be considered to develop optimal well maintenance and operation strategies.

It has been determined that the quantity of operations should be increased by 20% in wells located in the reservoir oxidation zone compared to wells located in non-oxidized (grey-colored) rocks. This approach allows optimizing repair-and-renewal processes of wells depending on their geochemical environment and increases mining efficiency in the field. The focus of this research is on the application of improved methods for assessing the efficiency of RROs and optimizing the technological repair-and-renewal processes of wells.

Directions for further research in this area may include analysis of the impact of different RRO methods on long-term well productivity.

4. Conclusions

The conducted research confirms that the operating mode of technological wells is dependent on a variety of factors, including both objective and subjective circumstances. Geologic peculiarities such as geochemical rock types, the ratio of extraction wells to injection wells, flow rate and injection capacity play an important role in uranium ISL process.

It has been found that the efficiency of the same RRO type can vary greatly depending on the stage of the leaching process and well operating time. Assessment of the efficiency of standard RRO types is necessary given the specific stage of the in-situ leaching process. Geotechnological parameters of ores and rocks also have a significant influence on the operation of technological wells. Correlation analysis shows that the quantity of conducted RROs has a direct relationship with the productivity of mineralization and an inverse relationship with the average filtration coefficient in the filter zone. The higher block productivity corresponds to a greater quantity of RROs performed in the wells.

The research results can be used in the application of geotechnological methods of uranium mining by ISL method through boreholes.

Author contributions

Conceptualization: KY, KR; Data curation: AO, AA; Formal analysis: AO; Funding acquisition: KR; Investigation: AO, AA; Methodology: KY, SM, MK, KR, SA; Project administration: KR; Resources: AO; Software: AO, AA; Supervision: KY, KR; Validation: KY, AO; Visualization: KY, AO; Writing – original draft: AO; Writing – review & editing: KY, SM, MK, KR, SA. All authors have read and agreed to the published version of the manuscript.

Funding

The work was carried out with the financial support of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan within the framework of program-targeted financing BR21881939 "Development of resource-saving energy-generating technologies for the mining and metallurgical complex and creation of an innovative engineering center".

Conflicts of interests

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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Дослідження впливу різних факторів на ремонтно-відновлювальні роботи на технологічних свердловинах при геотехнології урану у складних гірничо-геологічних умовах

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Мета. Підвищення ефективності та надійності ремонтно-відновлювальних робіт на технологічних свердловинах у складних гірничо-геологічних умовах, задіяних у підземному вилуговуванні урану, за рахунок виявлення та аналізу впливу геологічних, геохімічних і технічних факторів.

Методика. Дослідження базувалося на комплексному аналізі польових даних щодо конструкцій свердловин, характеристик порід та геохімічних умовах рудоносних горизонтів. Були проаналізовані параметри фільтрації, типи розкривних порід, склад робочих розчинів та особливості експлуатації свердловин з різною тривалістю роботи. Для систематизації факторів, що впливають на частоту та результативність ремонтних заходів, застосовувалися методи статистичного аналізу, включаючи кореляційний і регресійний аналізи. Результати зіставлялися з лабораторними експериментами, в яких оцінювалася ефективність різних хімічних реагентів з урахуванням мінерально-геохімічних особливостей уранових руд.

Результати. Проведений аналіз дозволив встановити, що інтенсивність ремонтно-відновлювальних робіт безпосередньо залежить від поєднання ряду факторів, серед яких найбільш значущими виявились геологічна будова рудовміщуючих порід та гідрохімічні умови руди. Показано, що при підвищеній продуктивності пласта збільшується потреба в частих ремонтно-відновлювальних операціях, що пояснюється активнішим режимом роботи і, отже, підвищеним навантаженням на експлуатаційні елементи. Виявлено характерні закономірності зміни коефіцієнта фільтрації та хімічного складу розчинів в інтервалах фільтрів, що дозволяють точніше прогнозувати терміни й обсяги необхідного ремонту.

Наукова новизна. Отримано залежність кількості ремонтно-відновлювальних робіт свердловин від продуктивності пласта, геохімічних умов руди на різних стадіях підземного свердловинного вилуговування урану.

Практична значимість. Отримані результати дають можливість інженерам і технологам розробляти більш надійні та гнучкі плани з обслуговування та ремонту свердловин з урахуванням конкретних геолого-гідродинамічних і геохімічних умов. Крім того, це знижує ризики аварійних ситуацій, але й підвищує загальний рівень видобутку урану за рахунок більш ефективного використання обладнання та робочих реагентів.

Ключові слова: *вилуговування урану, продуктивність видобутку, ремонтно-відновлювальні роботи, геологічні умови, рудовмісні породи, технологічні блоки*

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