Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 04, April, 2025

A Novel Process for Decolmatation of Wells During In Situ Leach Mining of Uranium

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Received 15 January 2025; Revised 11 March 2025; Accepted 18 March 2025; Published 01 April 2025

Abstract

The objective of this research is to enhance the efficiency of geotechnical wells by using a low-toxicity ammonium fluoride substance in neutral, acidic, and alkaline environments to dissolve colmatants. The research methodology includes X-ray spectral analysis, semi-quantitative X-ray phase analysis of the colmatants, laboratory experiments, and pilot-scale tests. The study results indicate that the use of ammonium fluoride combined with soda increases the dissolution of colmatants, particularly quartz, thereby improving the flow rate and extending the inter-repair cycle of process wells. When ammonium fluoride is used with sulfuric acid, it leads to a decrease in the oxidation-reduction potential (ORP), whereas its combination with soda ash increases the ORP, both of which positively affect the efficiency of in situ leaching technology for uranium mining. The practical significance and novelty of this work lie in the development of an effective and environmentally friendly decolmatation technology using a low-toxicity reagent—ammonium fluoride in combination with soda. For the first time, this research established the dependence of the degree of quartz colmatant dissolution on the concentration of ammonium fluoride in both acidic and alkaline environments, along with observed changes in ORP and pH values over time during treatment with alkaline and acidic solutions of ammonium fluoride.

Keywords: Colmatation; Repair-And-Renewal Operations; Chemical Treatment; Filter; Near-Filter Zone; Leaching; Ammonium Fluoride.

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1. Introduction

Nuclear fuel, a complex product with specific technology, is used to generate electricity in nuclear power plants. Currently, the extraction of raw materials for nuclear fuels is highly relevant. Depending on the efficiency and technology, there are three types of nuclear fuels: plutonium, thorium, and uranium. However, owing to the complexity of the production and processing of the first two and large reserves of uranium, it is used as a raw material for nuclear power plants. The largest producers of uranium are Kazakhstan, Canada, and Australia [1, 2]. A report by the International Atomic Energy Agency provides data on the increase in uranium production and demand due to the development of the global uranium industry [3]. The uranium industry in Kazakhstan is developing rapidly, improving every year, and playing a significant role in the global nuclear power industry. Since 2012, the Republic of Kazakhstan has ranked first in uranium mining, and the entire output is produced by the in situ leaching (ISL) technology of uranium mining using sulphuric acid solution [4-6].

In situ leaching technology is an efficient and low-cost method of uranium mining, involving the injection of leaching reagent directly into underground ore-bearing rock and removing the dissolved minerals through pumping out wells.

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http://dx.doi.org/10.28991/CEJ-2025-011-04-011

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This provides a complete chemical reaction between the uranium minerals and leaching reagent [7-9]. The leaching reagent promoted the formation of a liquid uranium-containing solution, from which uranium was extracted in the form of a metal.

Despite these advantages, this technology has a number of disadvantages, the main of which is a decrease in the performance of the production wells. As a rule, the reason for the decrease in well performance is the maturation of filters and near-filter zones of production wells [10-12]. Colmatation is the process of natural or artificial penetration of clay and dust particles into the pores and fractures of rocks into filters, as well as the deposition of chemical substances in them, contributing to a reduction in their infiltration capacity. In the near-filter zone, the colmatation process and accumulation of solid particles caused an increase in hydraulic resistance and a decrease in water inflow into the wells. The leaching of uranium minerals with sulphuric acid results in intensive carbonate sedimentation in the filter and near-filter zones. The main chemical leaching reaction occurring in the near-filter zone, uranite dissolution with sulphuric acid and conversion to uranyl sulphate, is shown in reactions 1 and 2.

$$\mathrm{UO_2 \cdot 2UO_3 + H_2SO_4 \rightarrow UO_2 + 2UO_2SO_4 + H_2O} \tag{1}$$

Simultaneously, the resulting $\mathrm{UO_2}$ is oxidized with trivalent iron ($Fe(OH)_3$) present in the rocks to produce divalent iron sulphate ($FeSO_4$) [13, 14]:

$$2Fe(OH)_3 + 3H_2SO_4 + UO_2 \rightarrow\ UO_2SO_4 + 2FeSO_4 + 6H_2O \tag{2}$$

The above chemical reactions are reversible, but the presence of silicates in the rocks contributes to the formation of the colmatation process. The predominance of quartz in the wells indicates that this species is a quartz-type colmatant. Quartz is an acidic oxide and therefore does not react with acids except hydrofluoric acid. Weak, poorly water-soluble silicic acids correspond to silicon dioxide. Silicic acid salts – silicates are insoluble in water, except for sodium and potassium silicates, which are widely used in in situ leaching technology for uranium mining in Kazakhstan.

Ongoing scientific studies have shown that addressing the deficiencies to improve the efficiency of uranium leaching and confronting the colmatant to meet the demand for uranium in nuclear power. The global, easily exploitable uranium reserves are 70% mined, so much research has focused on mining uranium from low-permeability deposits. For example, uranium can be mined from weakly permeable ores using low-frequency vibrations in CO_2 + O_2 [15] and surfactants [16]. The technology used in these studies is difficult to implement, as well as the high cost of surfactants. In addition, these methods focus on increasing ore-bearing formation permeability, which is extremely important in the uranium leaching process.

As is known, sulphuric nitric, and hydrochloric acids, soda, sodium bicarbonate (bicarbonate salts), and ammonium carbonate (salts and esters of carbonic acid) are used for uranium leaching. Since leaching involves the processing of large quantities of raw materials, the cost of leaching reagents largely determines the final product cost. Uranium mining enterprises in Kazakhstan use sulphuric acid as a reagent, the share of which makes up 27-45% of the operating costs for leaching. Therefore, various oxidizing agents are used to reduce the consumption of sulphuric acid, such as oxygen, ozone, hydrogen peroxide, chlorates, hypochlorites, and chloramines [17-20]. The use of these oxidizing agents contributes to increasing the efficacy of the uranium leaching process. However, these oxidizers require certain requirements for storage and transportation, leading to an increased cost of the final product and environmental consequences.

At present, in the uranium mines of Kazakhstan, injection wells are mainly flushed from mechanical colmatation, and pumping-out wells are mainly repaired and rehabilitated from chemical colmatation [21-24]. Colmatant control for pumping-out wells mainly involves chemical treatment with increased sulphuric acid and ammonium bifluoride $NH_4(HF_2)$ for quartz-type colmatants. Ammonium bifluoride forms hydrofluoric acid when it reacts with sulphuric acid solutions:

$$\mathrm{NH_4(HF_2) + H_2SO_4 = (NH_4)_2SO_4 + 4HF} \tag{3}$$

The hydrofluoric acid produced by the reaction dissolves the hard-soluble quartz compounds in the near-filter zone of the technological wells.

The disadvantage of using ammonium bifluoride for the chemical treatment of geological wells is the high toxicity of this reagent. According to the hazard class, $NH_4(HF_2)$ – VIII is a poison. It is a toxic substance for humans, flora, and fauna and has a strong corrosive effect. When transporting, storing, disposing, and using it, it is necessary to strictly adhere to the relevant rules, which leads to an increase in additional costs. Therefore, to solve the above disadvantages, this work conducted studies to establish low-toxicity substances, such as ammonium fluoride, in acidic and alkaline environments to dissolve colorants.

This paper includes materials and methods, results, discussion, conclusions, declarations, and references.

2. Materials and Methods

2.1. Materials

To study the proposed reagents and conduct laboratory tests, colmatants and mother liquor sampled from the Shu-Sarysu uranium deposits were examined. Quartz is selected as the basis for the colmatant under laboratory conditions (fused SiO_2, grade A, size: 0.5-0.2 mm, 99.70-99.99%, Xuzhou Sainuo Quartz Co.,Ltd.).

Chemical reagents used in this research:

- Ammonium fluoride (NH_4F 97.0%, Kanto Chemical Co., Inc);
- Sulphuric acid (H_2SO_4 95.0%, Juncei Chemical Co., Ltd);
- Soda ash (powdered Na_2CO_3, grade B, 98.5-99.4%, Bashkir Soda Company).

The chemical reagents were used in the laboratory tests as received without purification. All materials were stored in accordance with the prescribed safety and environmental standards, and the necessary precautions when handling chemicals were observed.

The flowchart of the research methodology is shown in Figure 1.

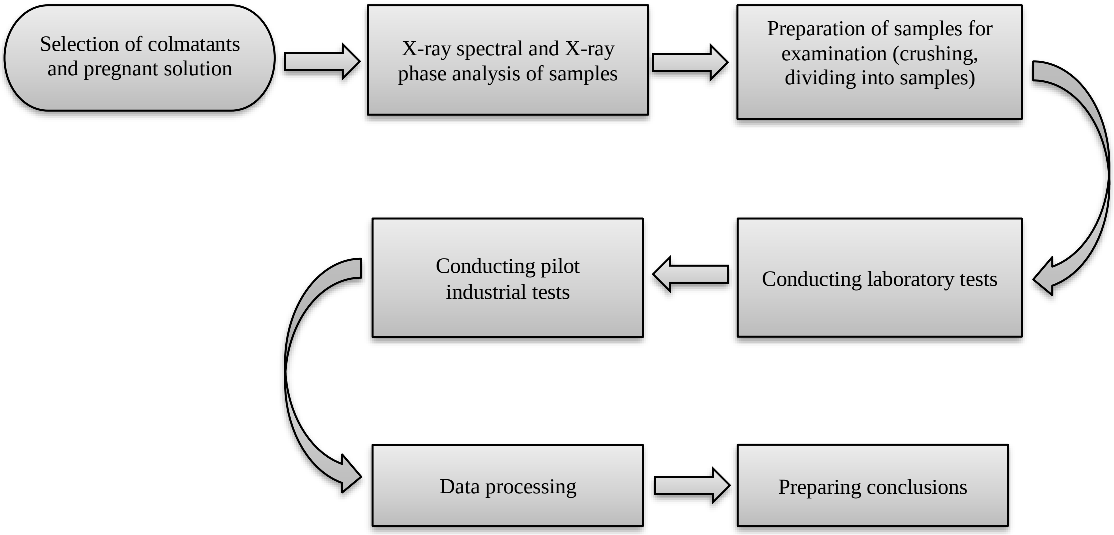

Figure 1. Flowchart of the research methodology

2.2. Material Characterization

X-ray spectral and semi-quantitative X-ray phase analyses were performed to study the composition of the colmatants. The elemental colmatant composition was studied on a Superprobe 733 electron-probe microanalyzer using an INCA ENERGY energy dispersion spectrometer at an accelerating voltage of 15 kV, probe current of 25 nA, and probe diameter of 1-2 µm. The following materials were used as reference samples: albite (Na), MgO (Mg), Al_2O_3 (Al), SiO_2(Si), adular (K), CaF_2(F), $CaSiO_3$(Ca), TiO_2(Ti), $Fe_2O_3 \cdot MnO$(Fe, Mn), and Cr_2O_3(Cr).

X-ray diffractometric analysis of the colmatant was conducted on a DRON-3 modernized automated diffractometer with $Cu_{K\alpha}$ –radiation, β-filter. Conditions for obtaining diffraction patterns: U=35 kV; I=20 mA; surveying θ-2θ; detector 2 deg/min. For X-ray diffractometric analysis, an analytical colmatant subsample crushed to a particle size of 0.05 mm.

2.3. Modification of Reagents

Ammonium fluoride is a colorless substance crystallizing in a hexagonal syngony and forming a wurtzite-type crystal lattice. This distinguishes it from other ammonium halogenides with cubic structures, which is due to the formation of strong hydrogen bonds in NH_4F and the immobility of NH^+ groups in the crystal. Ammonium fluoride differs significantly from other ammonium halogenides in terms of its reactivity. This is due to the specific properties of inorganic fluorides, particularly the high strength of element-fluorine bonds (large enthalpy of bond breaking) and, consequently, the significant values of enthalpies and Gibbs energies for many fluorination reactions. Owing to its specific characteristics, ammonium fluoride dissolves quartz, forms soluble fluorosilicates, and decomposes carbonate deposits by releasing carbon dioxide. It is worth noting that fluoride compounds can be toxic and accumulate. However,

NH_4 F decomposes into $NH_4{}^+$ and F^- ions, which can be neutralized or precipitated as poorly soluble safe compounds. The above characteristics of ammonium fluoride indicate that the product is a low-hazard reagent compared to other fluoride compounds, thereby reducing environmental risks. SiO_2 is also soluble in neutral and alkaline ammonium fluoride solutions with a relatively high rate of quartz dissolution when heated. Therefore, soda ash was chosen to produce an alkaline ammonium fluoride solution and dissolve quartz.

Sodium carbonate Na_2CO_3 is a medium salt of sodium and carbonic acid and is a white powder that is highly soluble in water. Soda ash is a hygroscopic product that absorbs water vapor and carbon dioxide in the air to form the acidic salt sodium hydrogen carbonate. Sodium carbonate is a water-soluble source of carbonate ions for Mg^{2+} and Ca^{2+}. These ions formed insoluble solid precipitates when treated with carbonate ions:

$$Ca^{2+} + CO_3^{2-} = CaCO_3$$

$$Ca^{2+}(aq) + Na_2CO_3(aq) = CaCO_3(s) + 2Na^+(aq) \tag{4}$$

$$Mg^{2+}(aq) + MgCO_3(aq) = MgCO_3(s) + 2Na^+(aq)$$

After treatment with sodium carbonate, the water softens because it no longer contains dissolved calcium and magnesium ions.

2.4. Modification of SiO_2 Powder Using NH_4F

Physicochemical analyses using the following instruments and equipment were carried out to modify quartz with ammonium fluoride: analytical balance, magnetic stirrer, 100 ml flasks, measuring vessels, separating funnel, tripod and drying cabinet, magnet for magnetic stirrer. In all tests performed under laboratory conditions, 9.67 g of SiO_2 and 100 ml of mother liquor served as the initial reagents.

3. Results

3.1. Laboratory Test

At the beginning of the laboratory test, the colmatant composition of the Syr-Darya province was examined by X-ray spectral analysis and semi-quantitative X-ray phase analysis (Tables 1 and 2).

Table 1. Results of X-ray spectral analysis of colmatant elemental composition from Syr-Darya province uranium deposits

O	Na	Mg	Al	Si	P	S	K	Ca	Fe
56.94	0.22	0.17	2.82	18.80	0.21	18.78	0.11	1.02	0.93

Table 2. Results of semi-quantitative X-ray phase analysis of the colmatant crystalline phases

Mineral	Formula	Concentration,%
Gypsum	$Ca(SO_4)(H_2O)_2$	3.3
Quartz	SiO_2	96.7

The elemental composition resulting from the analysis shows in Table 1 that the content of Si – 18.8%, O – 56.94%. The semi-quantitative X-ray phase analysis in Table 2 demonstrates the predominance of quartz (96.7%). The colmatant samples were then visually inspected. They are white-yellow-orange in color and exhibit continuous sedimentation. For the physicochemical analysis, the colmatants were crushed in an agate mortar to a powdery state. A material consisting of 9.67 g of quartz was used for further laboratory tests and colmatant analysis.

First, SiO_2 is physically mixed with ammonium fluoride. For example, 9.67 g of SiO_2 was mixed with 0.5 g NH_4F in 100 ml of mother liquor, and ammonium fluoride in a 1:1 ratio was added to sulphuric acid and soda ash. The mixed solutions were then left for 24 h at room temperature. The powders obtained after dissolution were flushed with deionized water at room temperature and dried under vacuum to remove traces of impurities. The resulting powders are named: acidic ammonium fluoride solution $SiO_2 – NH_4F – H_2SO_4$ and alkaline ammonium fluoride solution $SiO_2 – NH_4F – Na_2CO_3$. To compare the results, quartz was treated with ammonium fluoride (0.5 g) in 100 ml of mother liquor. After flushing with deionized water and drying under vacuum, the resulting purified powder was referred to as neutral ammonium fluoride solution $SiO_2 – NH_4F$ (Table 3).

Table 3. Laboratory tests

Parameter	First experiment	Second experiment	Third experiment
	$SiO_2 – NH_4F$	**$SiO_2 – NH_4F – H_2SO_4$**	**$SiO_2 – NH_4F – Na_2CO_3$**
Ammonium Fluoride Mass, g	0.5	0.5	0.5
	1.0	1.0	1.0
	1.5	1.5	1.5
	2.0	2.0	2.0
	2.5	2.5	2.5
	3.0	3.0	3.0
	Without adding acid and soda	Concentration of H_2SO_4 and Na_2CO_3 in 1:1 ratio with NH_4F	
Quartz Mass, g	9.67		

3.1.1. Laboratory Data Processing

The laboratory test results are shown in Table 4.

Table 4. Obtained results of quartz dissolution after treatment

Experiment	Quartz mass after dissolution, g					
First experiment (neutral ammonium fluoride solution)	6.33	5.75	4.97	3.68	2.99	1.74
Second experiment (acid ammonium fluoride solution)	9.63	9.62	9.59	9.57	9.55	9.51
Third experiment (alkaline ammonium fluoride solution)	4.23	3.42	2.97	2.04	1.52	0.50

As can be seen from Table 4, in the second experiment with an increase in ammonium fluoride concentration from 0.5 g to 3.0 g in the complex with sulphuric acid (acid medium), there was an insignificant degree of quartz dissolution of only 1.6%, in the first experiment in the complex with mother liquor, by 82%, and in the third experiment in the complex with calcined soda (alkaline medium), by 94.8%. Based on the data in Table 4, the dependence of the change in the degree of quartz dissolution from the ammonium fluoride concentration on the resulting quartz mass was determined (Figure 2).

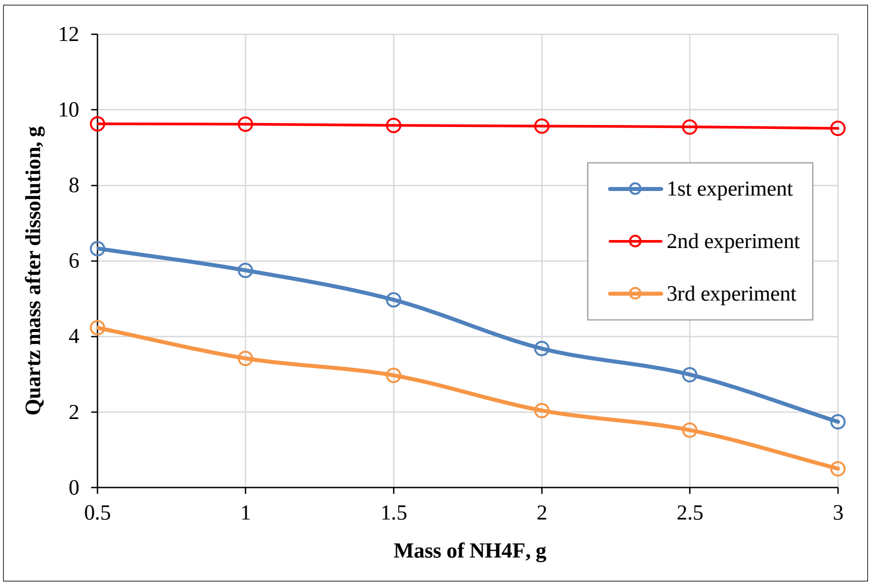

Figure 2. Dependency graph of ammonium fluoride concentration on the resulting quartz mass after dissolution (*Quartz mass after dissolution, g; Mass of NH_4F, g; 1st, 2nd, 3rd experiment)*

Considering Figure 2, it can be concluded that with an increase in the ammonium fluoride concentration, there was intensive quartz dissolution. Quartz is highly chemically inert, which means that it practically does not react with sulphuric acid, as shown by laboratory tests. When exposed to an alkaline ammonium fluoride solution, maximum quartz dissolution was achieved. Hydrolysis of ammonium salt with the mother liquor yields ammonium hydroxide and hydrofluoric acid Equation 5, and the interaction of soda with the aqueous mother liquor results in the formation of NaOH alkali Equation 6:

$$NH_4F + H_2O = NH_4OH + HF \tag{5}$$

$$Na_2CO_3 + H_2O = NaOH + CO_2 \uparrow \tag{6}$$

The action of hydrofluoric acid on quartz produces silicon fluoride (7), which in turn forms hydrofluosilicic acid and silicon dioxide (8).

$$SiO_2 + HF = SiF_4 + 2H_2O \tag{7}$$

$$3SiF_4 + 2H_2O = 2H_2SiF_6 + SiO_2 \tag{8}$$

Hydrofluosilicic acid is one of the strongest acids, and even in a very dilute aqueous solution, it has disinfecting properties. It is significantly stronger than hydrofluoric acid, and ammonium hydroxide (5) neutralizes it to form ammonium fluorosilicates.

$$2NH_4OH + H_2SiF_6 = (NH_4)_2SiF_6 + H_2 \uparrow \tag{9}$$

The obtained ammonium fluorosilicate is a colorless substance that is soluble in water (217.8 g/l at 26.7°C and 369.3 g/l at 68.3°C).

Based on the laboratory tests and the above-mentioned reactions, it can be considered that the most efficient dissolution of quartz was obtained using ammonium fluoride with soda ash in a ratio of 1:1. This experiment again showed that the dissolution of quartz in alkaline ammonium fluoride solutions obtained with the addition of soda ash facilitated dissolution.

3.2. Pre-Pilot Scale Test in Field

To study the effectiveness of ammonium fluoride application in the control of colmatants, experimental-industrial trials were conducted in the uranium deposit of the Shu-Sarysu province to find solutions to the above problems. Currently, it represents a long-term raw material base for uranium mining by the in situ leaching method in Kazakhstan [4, 25]. This deposit was chosen because the colmatant samples obtained from this mine have a predominance of quartz in their composition.

Four pumping wells (Table 5) were tested based on laboratory results. Particular attention was given to studying the effect of ammonium fluoride on key factors influencing the uranium leaching process, such as well flow rates, pH values, and oxidation-reduction potential (ORP). The ORP value was found to have a positive impact on the efficiency of in-situ uranium leaching [26]. The pH and ORP values obtained during the tests allow for tracing the influence of ammonium fluoride solutions on the $Fe^{3+}|Fe^{2+}$ ratio. A higher $Fe^{3+}|Fe^{2+}$ ratio corresponds to greater efficiency in the uranium leaching process [27, 28].

Table 5. Characteristics of pumping-out wells in the Shu-Sarysu uranium province

Well No.	Ammonium fluoride solution for chemical treatment	Flow rate at the time of well operation, m³/h	Block maturity, %	Filter length, m	MRC, day
1	Acid H_2SO_4	2.8	32.65 – 51.06	7.7	8
2		3.8		6.0	9
4	Alkaline Na_2CO_3	4.0		7.0	20-30
6		4.1		9.0	

Thus, 25 kg each of ammonium fluoride and sulphuric acid in 3000 l of mother liquor were used in 1-2 wells, and 25 kg each of ammonium fluoride and soda ash were used in 4-6 wells at a 1:1 ratio. The wells were monitored for 40-100 days and statistical data were collected.

3.2.1. Evolution of Eh and pH of wells

The pH and Eh values of the pregnant solution for leaching uranium with sulphuric acid after chemical treatment with acidic and alkaline ammonium fluoride solutions in the pumping-out wells are presented in Figures 3 and 4, respectively.

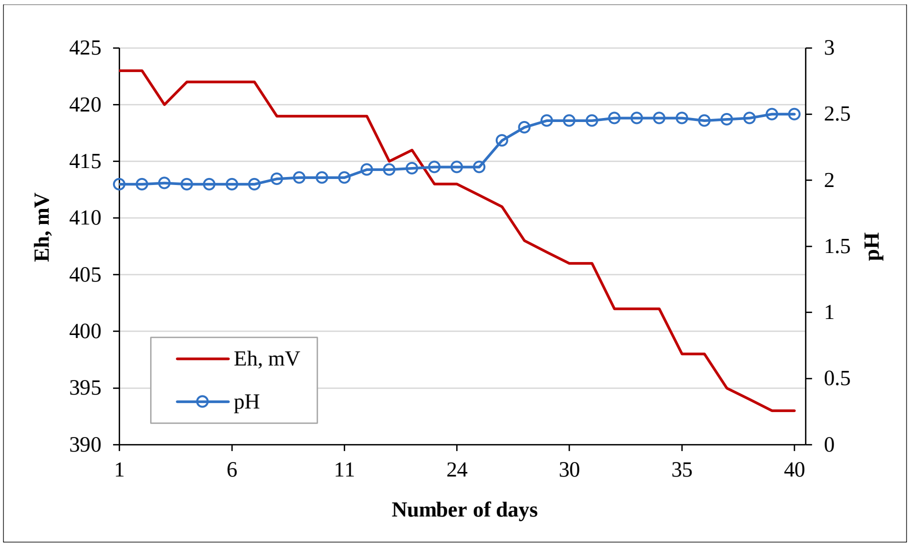

Figure 3. Graph of ORP and pH dependence for acidic ammonium fluoride solution

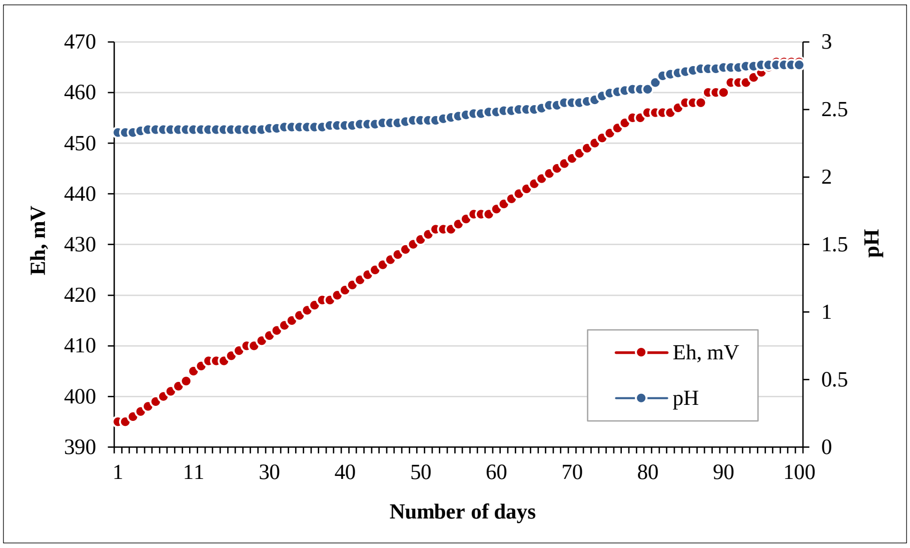

Figure 4. Graph of ORP and pH dependence for alkaline ammonium fluoride solution

Figures 3 and 4 show that when wells were chemically treated with acidic ammonium fluoride solution, the ORP value decreased, and when treated with alkaline ammonium fluoride solution, the ORP increased.

When the wells were chemically treated with an acidic ammonium fluoride solution for 40 days (Figure 3), the ORP decreased from 423 to 393 mV, and the pH increases from 1.97 to 2.50. This is due to the fact that this treatment produces hydrogen ion H^+, which, when interacting with acids, contributes to the formation of a divalent iron ion. In this case, there was an increase in the treatment time and additional costs during the leaching process.

Over 100 days (Figure 4), the ORP value of the alkaline ammonium fluoride solution increased from 395 to 466 mV, and the pH increases from 2.33 to 2.83, owing to the presence of oxygen in the hydroxyl group OH^- in the obtained alkali NaOH (6). The alkaline ammonium fluoride solution can increase the $Fe^{3+}|Fe^2$ ratio. NaOH alkali resulting from the hydrolysis of soda ash allows the conversion of divalent iron into a trivalent form. Trivalent iron ions, produced by the oxidation of divalent iron (2) with sulphuric acid, serve as strong oxidizing agents. Owing to its oxidizing properties, trivalent iron converts uranium oxide from the tetravalent to hexavalent form (1). When hexavalent uranium increased, the metal content and extraction in the pregnant solution increased, and the time of the well treatment was also reduced.

3.2.2. Current yield of wells

Further studies in experimental wells were conducted to determine the dynamics of the flow rate changes after using ammonium fluoride in acidic and alkaline solutions. The dynamics of the flow rate changes (Figures 5 and 6) in the experimental wells under consideration provides an analysis of the effectiveness of the proposed decolmatation technology. The flow rate in geotechnical wells directly depends on the amount of metal extracted because an unplanned decline in the flow rate will negatively affect the annual production of uranium.

In wells No. 1 and No. 2, chemical treatment with ammonium fluoride and sulphuric acid was carried out, and monitoring was carried out for 40 days until the pump was stopped according to the specified flow rate regulations for well undermine conditions. In wells No. 4 and No. 6, chemical treatment with ammonium fluoride and soda ash was carried out, and observations were carried out for 100 days until the pump was stopped according to the specified flow rate regulations for well undermine conditions.

Figures 5 and 6 show the changes in the well flow rate with different well decolmatation methods.

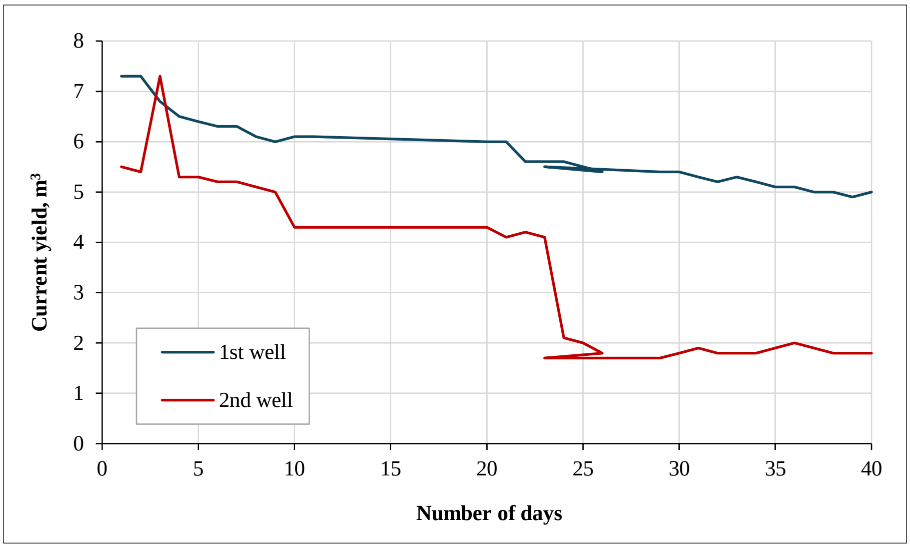

Figure 5. Dependency graph of flow rate on the number of days of acidic ammonium fluoride solution

According to Figure 5, during chemical treatment with an acid solution of ammonium fluoride for 22 days, there is a slight decrease in the flow rate of the first and second wells from 7.3 m^3 to 6.0 m^3 and from 5.5 m^3 to 4.2 m^3, respectively. With a further increase in the amount to 40 days, there was a significant decrease in the flow rate of the wells to 5 m^3 and 1.8 m^3, respectively. If so, when treating wells with an acid solution of ammonium fluoride, the overhaul cycle is slightly more than 20 days. The decrease in the flow rate with an acid solution can also be explained by a sharp decrease in the ORP value (Figure 3).

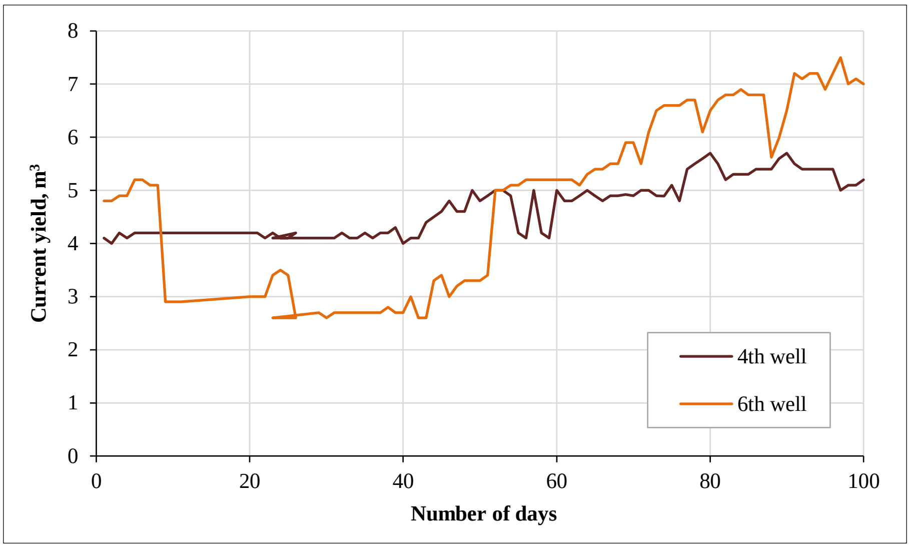

Figure 6. Dependency graph of flow rate on the number of days of alkaline ammonium fluoride solution

During chemical treatment with an alkaline ammonium fluoride solution (Figure 6) within 100 days, there is an increase in flow rate in the fourth well from 4.1 m^3 to 5.0 m^3, in the sixth well – from 4.8 m^3 to 7.0 m^3. Thus, it can be concluded that when using an alkaline solution of ammonium fluoride, the inter-repair cycle increases by five times compared to when using an acidic solution of ammonium fluoride. This can be explained by the increase in the ORP and pH when using an alkaline solution of ammonium fluoride (Figure 4). Figures 5 and 6 also show a critical decrease in the flow rate due to the coloration of the near-filter zone. However, despite this, the chemical treatment of wells allows the maintenance of metal production at the level of planned indicators for the Shu-Sarysu province mines.

4. Discussion

The efficiency of the alkaline ammonium fluoride solution was higher than that of the acidic ammonium fluoride solution. The analysis of graphs testifies to the prospective use of alkaline ammonium fluoride solution with sodium carbonate for decolmatation of wells, which increases the flow rate and inter-repair cycle of wells.

Compared to the currently used ammonium bifluoride for the chemical treatment of geotechnological wells, the proposed ammonium fluoride reagent increases the productivity of treated wells, as well as the inter-repair cycle of their operation. In particular, the inter-repair cycle of wells has more than doubled, from an average of 30 days to 70 days; flow rate in the first well increases from 2.8 m^3 to 7.3 m^3, in the second well – from 3.8 m^3 to 5.5 m^3, in the third well – from 4.0 m^3 to 5.0 m^3, in the fourth well – from 4.1 m^3 to 7.0 m^3, respectively. And with airlift flushing of wells, the inter-repair cycle is 18 days, the well flow rate is on average 2.6 $m^3/$h [4, 25].

The research results are unique in that the values obtained in chemical treatment are constant for an average of 30-70 days, contributing to an efficient flow of the leaching process and leading to a reduction in the cost of mined uranium and additional costs for repair and renewal operations.

A comparative analysis of the flow rate and inter-repair cycle of wells treated with concentrated sulphuric acid, ammonium bifluoride [4], NTF-targeted inhibitors [29], and ammonium fluoride (proposed technology) is given in Table 6.

Table 6. A comparative analysis of the flow rate and the inter-repair cycle of wells

Indicators	The well flow rate, $m^3/$h	The inter-repair cycle of wells, day
Treatment with concentrated sulphuric acid	3,3	9
Treatment with ammonium bifluoride	3,8	26
NTF-targeted inhibitors	4,2	22
Treatment with ammonium fluoride (Proposed technology)	4,05	30

Based on the data in Table 6, it can be concluded that with the proposed technology, there is an increase in the well flow rate of process wells by 23% compared to treatment with concentrated sulphuric acid and by 6.6% with ammonium bifluoride, and the inter-repair cycle of wells by 233% and 15.4%, respectively.

Based on the data in Table 6, it can be concluded that the best flow rate indicators of 4.2 $m^3/$h is achieved with the use of inhibitors, but the operating time between repairs is 26% less than that of the proposed technology. The proposed technology shows an increase in the well flow rate of process wells by 23% compared to treatment with concentrated sulphuric acid and 6.6% with ammonium bifluoride, and the inter-repair cycle of wells by 233% and 15.4%, respectively. A previous study by Kenzhetaev et al. [29] established that when inhibitors are used, uranium extraction during sorption is reduced by 6% owing to the formation of a thin monomolecular film on the surface of the sorbent.

It should be stressed that, at present, the prices of ammonium bifluoride are twice as high as those of the proposed low-toxic substances, which contributes to the rise in the cost of the in situ leaching process. Ammonium bifluoride is also a dangerous and poisonous reagent that directly impacts the environmental situation in the regions and human health. Added to this is atmospheric pollution and reduced soil fertility, resulting in the loss of the ability of polluted soil to support flora and fauna.

The use of ammonium fluoride with soda ash instead of poisonous and dangerous substances is environmentally safe and effective. Prospects for further research in this direction include the implementation and development of a methodology for using an alkaline ammonium fluoride solution in the uranium fields of Kazakhstan to improve the productivity of geotechnological wells.

5. Conclusion

X-ray spectral and semi-quantitative X-ray phase analyses made it possible to identify the elemental composition of the colmatant and to determine the type of colmatation process. Physicochemical analysis helped to understand the degree of dissolution of colmatants in different chemical media released by the addition of different additives to the leaching solution, which made it possible to identify the chemical reagents used in the required concentrations and ratios. The novelty of this study lies in the development of a new technology for the decolmatation of filters and the near-filter zone of wells using a low-toxicity reagent in the form of ammonium fluoride in combination with soda, which will increase the flow rate and the inter-repair cycle of wells. The results of this study made it possible to determine the dependence of the degree of dissolution of the colmatant in the form of quartz on the concentration of ammonium fluoride in acidic and alkaline environments. A comparative analysis of changes in the ORP and pH values during the treatment of colmatants with alkaline and acidic solutions of ammonium fluoride over time proved the effectiveness of ammonium fluoride in combination with an alkaline solution.

The obtained results can be used not only for the in situ leaching of uranium, but also for the heap leaching of metals and oil production. The proposed decolmatation technology effectively dissolves chemical colmatation using a low-toxicity reagent, increases the flow rate and inter-repair cycle of wells, and reduces the period of uranium reserve development. This will reduce the cost of the final product and thus increase its competitiveness in the global market. Prospects for further research in this direction include the implementation and development of a methodology for using an alkaline ammonium fluoride solution in the uranium fields of Kazakhstan to improve the productivity of geotechnological wells.

6. Declarations

6.1. Author Contributions

Conceptualization, Kh.Y. and E.A.; methodology, Kh.Y.; software, G.A.; validation, D.A., E.Y., and G.A.; formal analysis, E.A.; investigation, S.M.; resources, E.A.; data curation, S.M.; writing—original draft preparation, Kh.Y., S.M., and E.Y.; writing—review and editing, E.A., D.A., and G.A.; visualization, D.A. and E.Y.; supervision, Kh.Y.; project administration, E.A.; funding acquisition, E.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

This research is funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19679911 - “Increasing the efficiency of uranium leaching in the development of complex hydrogenic deposits”).

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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