GEOCHEMICAL PROPERTIES OF URANIUM AND ITS MIGRATION ABILITY IN NATURAL ENVIRONMENTS

Sharafutdinov Ulugbek Ziyatovich
Director of the Advanced Technologies Center, Navoi Mining and Metallurgical Combine Joint-Stock Company (NMMC JSC).
E-mail: u.sharafutdinov@ngmk.uz
Khalimov Ilkhom Ubaydullayevich
Professor, Faculty of Mining, Head of department RRM, Navoi State University of Mining and Technologies.
E-mail: halimov_i@bk.ru
Yuldashev Shokhrukh Shonazar ugli
Associate Professor, Faculty of Mining, Department of RRM, Navoi State University of Mining and Technologies.
E-mail: mryuldashevshohruh@gmail.com
Serveriyeva Umida Sherzod qizi
Master's student, Faculty of Mining, Department of RRM Navoi State University of Mining and Technologies.
E-mail: serveriyevaumida@gmail.com

Annotatsiya. Maqolada uranning geokimyoviy xossalari va uning tabiiy suv–tuproq tizimlarida migratsiya xatti-harakati tahlil qilingan. Uran eng barqaror holatda olti valentli shaklda bo‘lishi va suvli eritmalarda asosan uranil ioni hamda uning kompleks birikmalari ko‘rinishida uchrashi ko‘rsatilgan. pH muhiti, oksidlanish-qaytarilish sharoitlari (Eh), shuningdek karbonat, sulfat va fosfat ionlari konsentratsiyasining uranning shakllanishi va eruvchanligiga ta’siri o‘rganilgan. Neytral va biroz ishqoriy karbonatli muhitda uran (VI) yuqori harakatchanlikka ega bo‘lgan barqaror anion karbonat komplekslarini hosil qilishi aniqlangan. Uraning temir va marganes oksidlari hamda gil minerallarida sorbsiyalanish jarayonlari, shuningdek organik moddalarning humat va fulvat komplekslarini hosil qilishdagi roli ko‘rib chiqilgan. To‘rt valentli uran past eruvchanlik va harakatchanlik bilan tavsiflanib, yomon eriydigan minerallarni hosil qiladi. Natijalar tabiiy muhitda uran migratsiyasini boshqarishda kompleks hosil bo‘lish va redoks jarayonlarining hal qiluvchi rolini tasdiqlaydi.

Kalit so‘zlar: uran, uranil ioni, geokimyoviy xossalar, uran migratsiyasi, Eh–pH diagrammasi, komplekslanish, karbonat komplekslari, sorbsiya, kremniy va tabiiy suvlar.

Аннотация. В статье анализируются геохимические свойства урана и особенности его миграционного поведения в природных водно-почвенных системах. Показано, что уран наиболее устойчив в шестивалентном

ISSN 3030-3907

состоянии и в водных растворах присутствует преимущественно в виде уранильного иона и его комплексных соединений. Рассмотрено влияние pH среды, окислительно-восстановительных условий (Eh), а также концентраций карбонатных, сульфатных и фосфатных ионов на формы существования и растворимость урана. Установлено, что в нейтральных и слабощелочных карбонатных условиях уран (VI) образует устойчивые анионные карбонатные комплексы с высокой подвижностью. Рассмотрены процессы сорбции урана на оксидах железа и марганца, а также на глинистых минералах, и роль органического вещества в образовании гуматных и фульватных комплексов. Четырёхвалентный уран характеризуется низкой растворимостью и подвижностью, образуя плохо растворимые минералы. Полученные результаты подтверждают ключевую роль процессов комплексообразования и окислительно-восстановительных реакций в контроле миграции урана в природных условиях.

Ключевые слова: уран, уранильный ион, геохимические свойства, миграция урана, диаграмма Eh–pH, комплексообразование, карбонатные комплексы, сорбция, почвы и природные воды.

Abstract. The article analyzes the geochemical properties of uranium and its migration behavior in natural water–soil systems. It is shown that uranium is most stable in the hexavalent state and occurs in aqueous solutions mainly as the uranyl ion and its complex compounds. The influence of pH, redox conditions (Eh), and the concentrations of carbonate, sulfate, and phosphate ions on uranium speciation and solubility is examined. It is established that in neutral and slightly alkaline carbonate environments, uranium (VI) forms stable anionic carbonate complexes with high mobility. The processes of uranium sorption on iron and manganese oxides as well as clay minerals are considered, along with the role of organic matter in the formation of humate and fulvate complexes. Tetravalent uranium is characterized by low solubility and mobility, forming poorly soluble minerals. The results confirm the key role of complexation and redox processes in controlling uranium migration in natural environments.

Keywords: uranium, uranyl ion, geochemical properties, uranium migration, Eh–pH diagram, complexation, carbonate complexes, sorption, soils and natural waters.

INTRODUCTION

Uranium is one of the most important elements in nuclear energy production and occurs in natural environments in various chemical forms. Its behavior in water–soil systems is controlled by complex geochemical processes, including oxidation–reduction reactions, complexation, and sorption. Understanding the

ISSN 3030-3907

geochemical properties of uranium and the mechanisms governing its migration is essential for evaluating uranium ore formation, predicting its mobility in the environment, and ensuring environmental safety.

In natural conditions, uranium mainly exists in hexavalent and tetravalent states, with uranium(VI) being significantly more soluble and mobile. The speciation and migration of uranium strongly depend on pH, redox potential (Eh), mineral composition, and the presence of carbonate, sulfate, phosphate ions, and organic matter. Especially in carbonate-rich environments, uranium(VI) forms stable anionic complexes that enhance its mobility over long distances.

The growing application of in-situ leaching technologies in uranium mining has increased the relevance of studying uranium geochemistry in natural and technogenic systems. Therefore, this article focuses on analyzing the geochemical properties of uranium, its migration behavior under different Eh–pH conditions, and the role of complexation and sorption processes. The scientific novelty of this study lies in the integrated assessment of the factors controlling uranium mobility in natural environments, which provides a theoretical basis for uranium extraction technologies and environmental risk assessment.

Analysis of the Geochemical Properties of Uranium. Uranium is most stable in the +6 oxidation state and, in aqueous solutions, forms the uranyl ion (UO_2^{2+}), which has a compact linear structure. Due to its large ionic radius, the uranyl ion does not substitute for natural cations but instead forms its own minerals, such as uraninite and nasturan.

Uranium(VI) compounds are generally well soluble, particularly nitrates, sulfates, and oxyhalides, which, upon contact with steam, are converted into oxyhalides. Poorly soluble compounds include phosphates, arsenates, and vanadates.

In nature, uranium(VI) predominantly occurs in the form of complex compounds with coordination numbers of 4 and 6. The most significant among them are carbonate, sulfate, fluoride, phosphate, and hydroxo complexes. Their ability to form complexes decreases in the following order:

-monovalent ligands: $F^- > NO_3^- > Cl^- > ClO_4^-$;

-divalent ligands: $CO_3^{2-} > C_2O_4^{2-} > SO_4^{2-}$.

Migration Capacity of Uranium. The migration capacity of uranium is determined by its solubility, which depends on pH, redox conditions, temperature, soil composition, and the activity of microorganisms. In soils, uranium occurs in precipitated, reduced, or sorbed forms, and its mobility is governed by its specific chemical state. Carbonate and sulfate complexes of uranium exhibit high solubility and are capable of migrating over considerable distances.

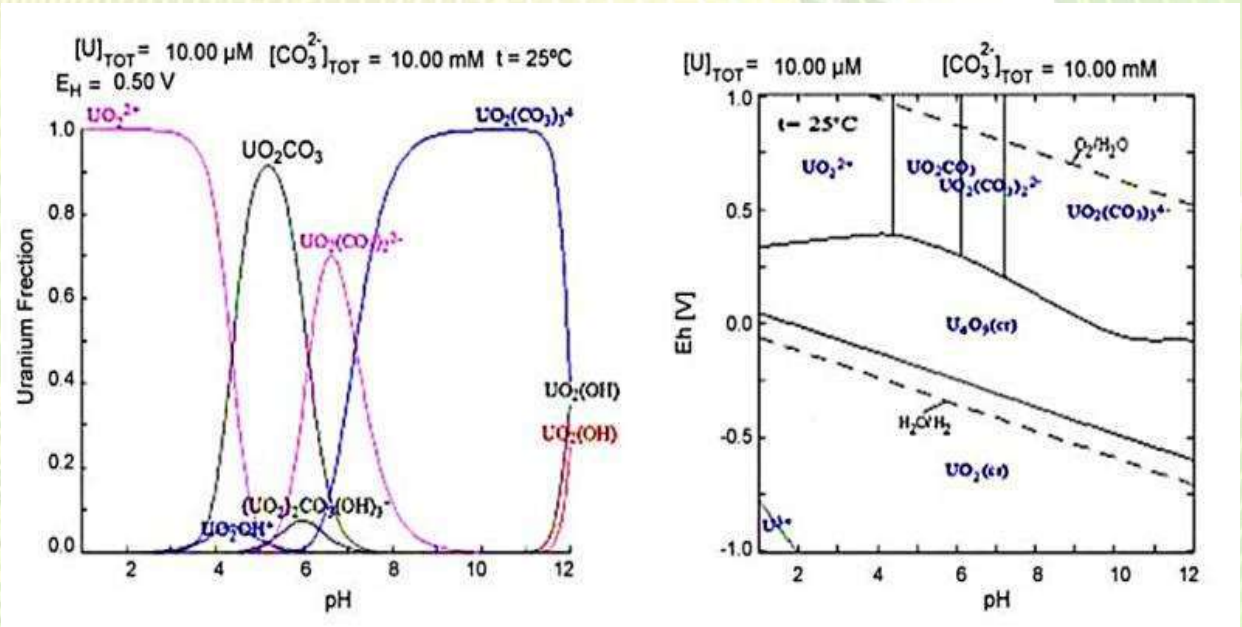
ISSN 3030-3907

Uranium occurs in nature in both hexavalent and tetravalent forms. In soils, it is usually present in an oxidized state, while in aqueous environments it exists mainly as uranyl–hydroxo–carbonate complexes. Its accumulation in soils takes place through adsorption, chemisorption, and ion exchange, whereas its mobility is controlled by complexation processes and redox reactions.

Hexavalent uranium is predominantly present in solutions in the form of the uranyl ion and carbonate complexes. In soils with pH values of 4.0–7.5, it occurs mainly in hydrolyzed forms, whereas tetravalent uranium is weakly mobile, forming sparingly soluble minerals such as uraninite. Under reducing conditions, dissolved uranium(III) is rapidly oxidized to uranium(IV), while uranium(V) undergoes disproportionation to form a mixture of uranium(IV) and uranium(VI). Thermodynamic calculations indicate the existence of an interrelationship between tetravalent and hexavalent uranium under weathering conditions and in hydrothermal solutions.

$$U^{4+} + 2H_2O = UO_2{}^{2+} + 4H^+ + 2e^- \quad logK_o = -9{,}038 \qquad (1.1)$$

Uranium(VI) exhibits significantly higher solubility and mobility than uranium(IV). Figure 1 illustrates its speciation at 25 °C as a function of pH and redox conditions. In natural environments, hydroxide and carbonate complexes prevail, along with tetravalent and hexavalent forms of uranium. In neutral and slightly alkaline carbonate waters, uranium(VI) occurs in the form of stable anionic carbonate complexes such as UO_2CO_3, $UO_2(CO_3)_2^{2-}$, and $UO_2(CO_3)_3^{4-}$.



ISSN 3030-3907

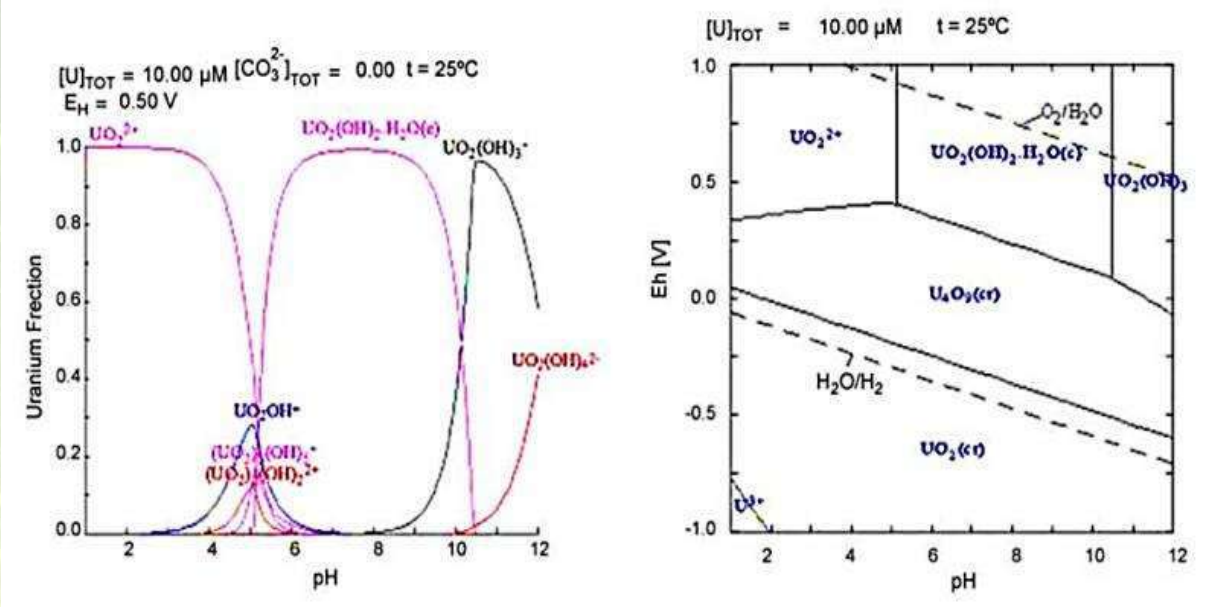


Fig. 1. Dependence of uranium speciation on Eh–pH conditions.

Within the pH range of 7–8, uranium is predominantly present in the form of the carbonate complex $UO_2(CO_3)_2^{2-}$ (Fig. 1a). In carbonate-rich environments, its adsorption onto minerals decreases, which promotes the release of uranium from soils. At low redox potential (Eh) values, uranium precipitates, whereas at high Eh values, dissolved carbonate complexes prevail. At Eh > 0.25 V and pH 7–8, uranium occurs in the oxidized hexavalent form, while in acidic media (pH 1–5) at the same potential it exists as the uranyl ion $[UO_2]^{2+}$. In alkaline environments, carbonate ions enhance its solubility. Figure 2 illustrates the effect of CO_2 concentration and pH on uranium speciation: carbonate complexes can form even under reducing conditions when carbonate concentrations are high.

Hydroxo complexes, such as $UO_2(OH)^+$ and $(UO_2)_3(OH)_5^+$, may also occur; however, their contribution is minor. These species form at elevated temperatures or in alkaline environments with low carbonate content. Tetravalent uranium is poorly soluble and is prone to hydrolysis and colloid formation. Modeling of Eh–pH diagrams is further complicated by the influence of Ca^{2+} and Mg^{2+} ions and by the formation of sulfate complexes.

In acidic environments (pH < 6), uranium may remain in solution as $[(UO_2)_3OH]^{5+}$ rather than precipitating as carbonates. In the presence of carbonate and sulfate anions, phosphate complexes (UO_2HPO_4, $UO_2PO_4^-$) become predominant and can persist at pH values above 8.

Although sulfate, fluoride, and chloride complexes are less stable, they are important for understanding uranium speciation in aqueous environments. Figures 3–5 demonstrate that increasing pH and decreasing Eh significantly alter the conditions of uranium migration and precipitation.

ISSN 3030-3907

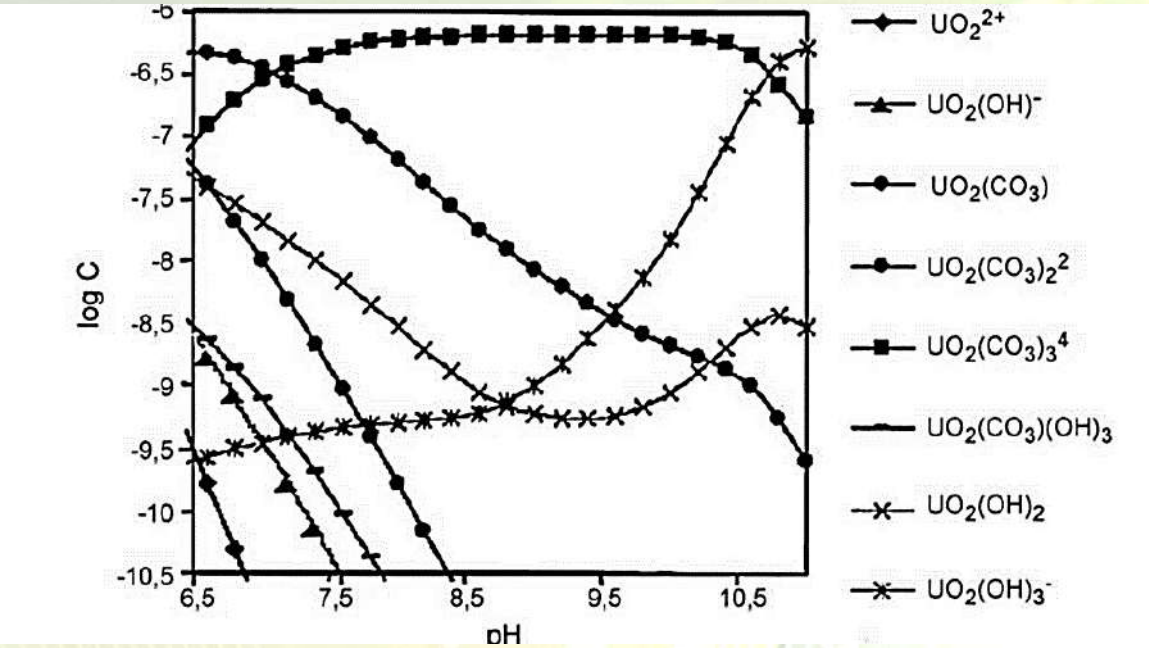


Fig. 2. Effect of pH and carbon dioxide concentration on the chemical forms of uranium in natural waters

Under natural conditions, uranium actively interacts with organic matter. Humic and fulvic acids, which are widely distributed in the natural environment, form humate and fulvate complexes with uranium, the solubility of which depends on the acidity (pH) of the medium.

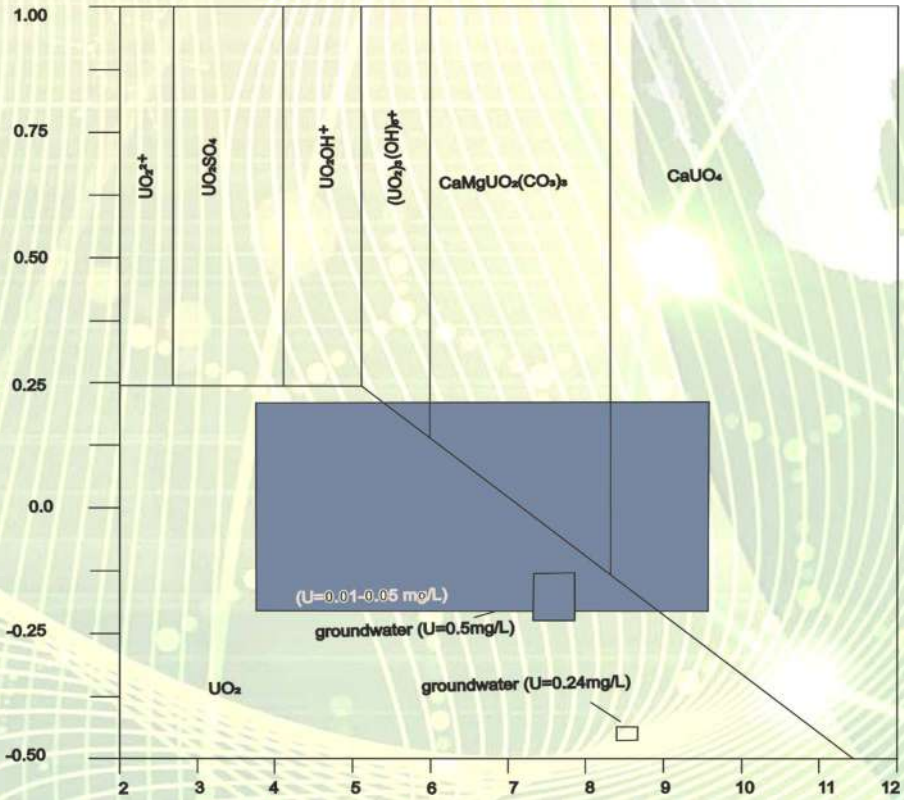


Fig. 3. Eh–pH diagram of uranium (0.01–0.5 mg/L) in dolomitic water

ISSN 3030-3907

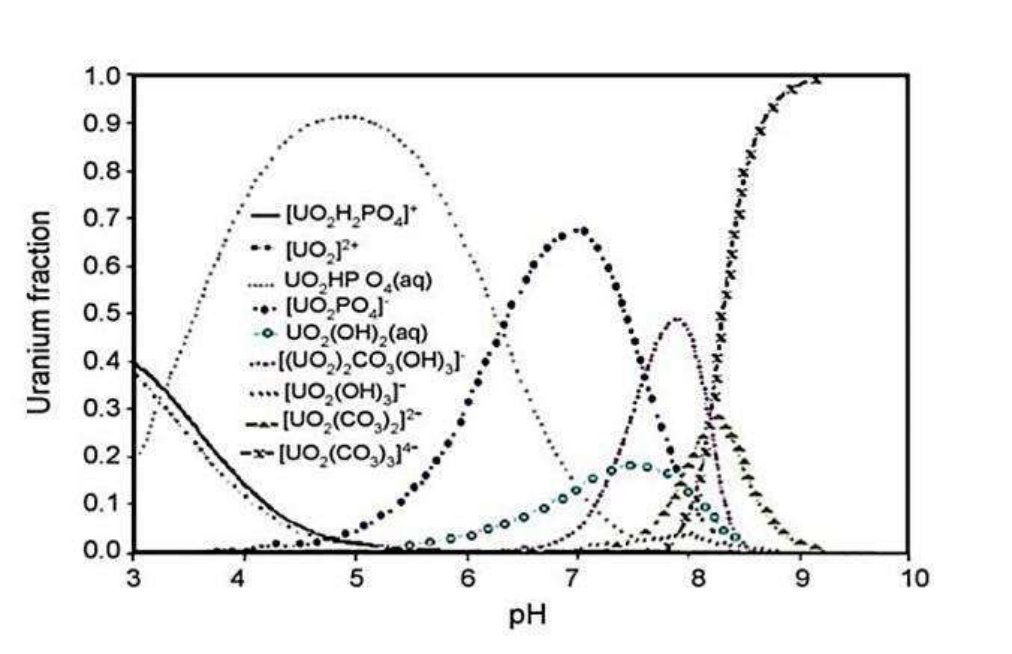


Fig. 4. Calculated fractional distribution of various uranium species in the UO_2–PO_4–CO_3–OH–H_2O system at t = 25 °C

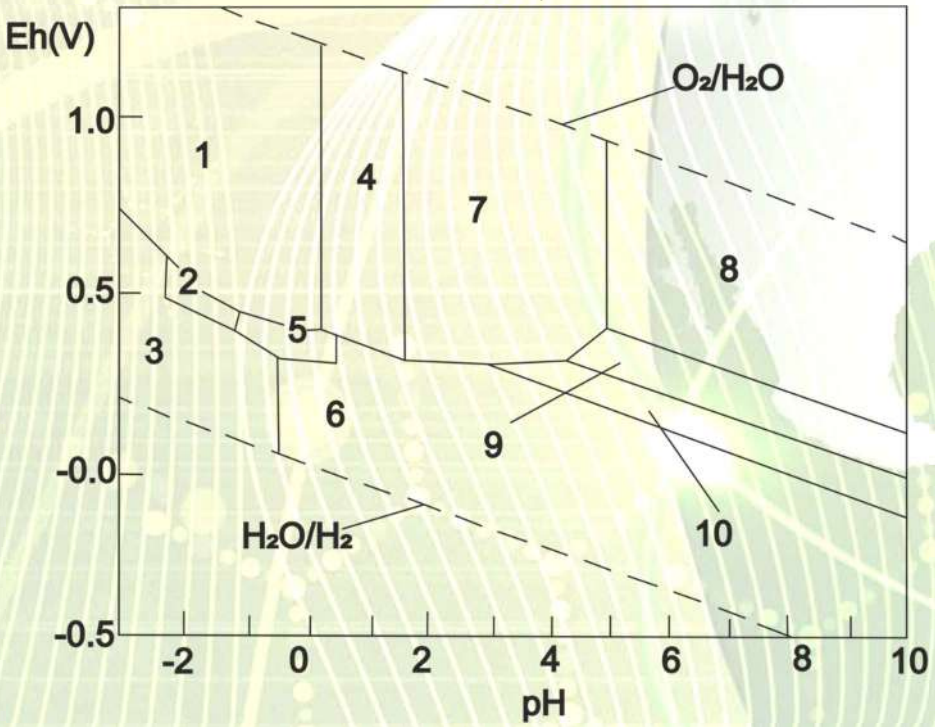


Fig. 5. Eh–pH diagram and uranium speciation in the presence of sulfates at t = 25 °C; uranium ion concentration 0.01 mg/L; sulfate ion concentration: 0.1 mg/L. (1) UO_2^{2+}; (2) $U(SO_4)^{2+}$; (3) U^{4+}; (4)UO_2SO_4; (5)$UO_2(SO_4)_2$; (6)UO_2; (7)$UO_2(SO_4)_2^{2-}$; (8)$UO_2(OH)_2 \cdot H_2O$; (9)U_3O_8; (10) U_4O_9.

Hexavalent uranium in soils is adsorbed onto iron and manganese oxides as well as clay minerals through interactions with hydroxyl groups and aluminosilicate frameworks. Sorption strongly depends on pH: at low pH values, H^+ ions compete with the uranyl ion, leading to the formation of a positively

ISSN 3030-3907

charged surface layer ($–Si–OH_2^+$), whereas with increasing pH, uranium binds to surface hydroxyl groups.

Maximum adsorption of uranium onto goethite and ferrihydrite is observed at pH 4–5, while at neutral pH values, sorption of the uranyl ion on carbonate-bearing surfaces predominates. Goethite is also capable of adsorbing carbonate–sulfate complexes such as $[UO_2CO_3SO_4]^{2-}$ and tricarbonate complexes $[UO_2(CO_3)_3]^{4-}$.

According to the data reported by Payne and White, amorphous iron hydroxides ($Fe_2O_3 \cdot H_2O$) are able to sorb not only neutral carbonate complexes UO_2CO_3 but also bicarbonate complexes $[UO_2(CO_3)_2]^{2-}$, as well as tricarbonate complexes $[UO_2(CO_3)_3]^{4-}$. Subsequently, Waite et al. confirmed the sorption capacity of ferrihydrite toward UO_2CO_3. Studies by Duff and Amrhein demonstrated that goethite can sorb the anionic complex $[(UO_2)_2CO_3(OH)_3]^-$. In addition, spectroscopic analyses reported in these studies revealed the formation of ternary uranium–carbonate surface complexes of the type $[\equiv SO–UO_2(CO_3)_x]$ on mineral surfaces such as hematite and quartz.

REFERENCES:

1. Шарафутдинов Улугбек Зиятович, Ражаббоев Ибодулла Муродуллаевич, Эшонова Гулноза Алиевна, & Юлдашев Шохрух Шоназар Угли (2023). Исследования влияния фосфат ионов на процесс получение урана. Universum: технические науки, (7-4 (112)), 5-9.

2. Ulugbek Sharafutdinov, Ilkhom Karimov, Ibodulla Rajabboev, Shokhrukh Yuldashev, Madina Khamidova and Dilnoza Khurramova. “Presence and impact of silica and organics in uranium in-situ leaching solutions”, E3S Web Conf., 627 (2025) 01011. DOI: https://doi.org/10.1051/e3sconf/202562701011.

3. Ulugbek Sharafutdinov, & Shohruh Yuldashev (2023). Methods of reducing the depressing effect of the silicon bond during selective dissolution underground. Universum: технические науки, (10-7 (115)), 12-15. doi: 10.32743/UniTech.2023.115.10.16072

4. Zhang, C.; Li, Z.; Peng, H.; Wu, Y.; Luo, N.; Pang, K.; Qiu, Z.; Yu, X.; Quan, H.; Wang, M.; et al. Provenance Tracing of Uranium-Bearing Sandstone of Saihan Formation in Naomugeng Sag, Erlian Basin, China. Minerals 2026, 16, 76. https://doi.org/10.3390/min16010076

5. Lai, J., Zhong, F., Qiu, L., Li, G., Liu, W., Wang, H., & Xia, F. (2026). Age and Origin of Mafic Dykes in the Mianhuakeng Uranium Deposit, South China: Tectonic and Metallogenic Implications. Minerals, 16(1), 54. https://doi.org/10.3390/min16010054

6. Abd El-Naby, H. H., Dawood, Y. H., & Sabtan, A. A. A. (2026). Uranium

ISSN 3030-3907

Isotopic Fractionation and Hydrogeochemical Controls in Groundwater of the Jabal Sayid–Mahd Adhab Region, Western Saudi Arabia. Minerals, 16(1), 25. https://doi.org/10.3390/min16010025

7. Fang, Z., Gan, M., Zhang, L., Wang, Y., & Fu, X. (2026). Feasibility and Challenges of In Situ Uranium Leaching Using Ozone Bubbles: A Review. Minerals, 16(1), 2. https://doi.org/10.3390/min16010002

8. Nie, Z., Gu, S., Zhou, A., Guo, C., Peng, H., Wang, H., Li, L., Wang, Q., Hao, Y., Liu, H., & Liu, C. (2025). The Role of OM in the Formation of Sandstone-Type Uranium Ore—A Review. Minerals, 15(12), 1326. https://doi.org/10.3390/min15121326

9. Haidouri, M., Ait-Khouia, Y., Elghali, A., El Ghorfi, M., Benzaazoua, M., & Taha, Y. (2025). Phosphate Waste Rock Piles as a Secondary Resource: Insights into Composition and Strategic Element Potential. Minerals, 15(12), 1319. https://doi.org/10.3390/min15121319

10. Zhang, X., Che, J., Nie, F., Miao, A., Yan, Z., Zhang, C., & Hu, Y. (2025). Provenance and Uranium Sources in the Lower Cretaceous Huanhe Formation of Northern Ordos Basin: Constraints from Detrital Zircon U–Pb Geochronology and Hf Isotopes. Minerals, 15(10), 1079. https://doi.org/10.3390/min15101079

11. Kurmanseiit, M., Shayakhmetov, N., Aizhulov, D., Tleuberdy, A., Abdullayeva, B., & Tungatarova, M. (2025). Comparative Evaluation of Flow Rate Distribution Methods for Uranium In-Situ Leaching via Reactive Transport Modeling. Minerals, 15(10), 1066. https://doi.org/10.3390/min15101066

12. Fu, Z., Zheng, X., Yan, Y., Xu, X., Zhou, F., Li, X., Zhou, Q., & Mai, W. (2025). The Evolution of Machine Learning in Large-Scale Mineral Prospectivity Prediction: A Decade of Innovation (2016–2025). Minerals, 15(10), 1042. https://doi.org/10.3390/min15101042

13. Fathy, D. M., Abanumay, F. A., Ali, S., Farahat, E. S., Bekker, A., & Azer, M. K. (2025). An Occurrence of Pyroxmangite in the NYF Granitic Pegmatite of the Gabal El-Bakriya Intrusion, Arabian–Nubian Shield. Minerals, 15(10), 1027. https://doi.org/10.3390/min15101027

14. Habibi, Z., Cook, N. J., Ehrig, K., Ciobanu, C. L., Campo-Rodriguez, Y. T., & King, S. A. (2025). Minor and Trace Elements in Copper Tailings: A Mineralogical and Geometallurgical Approach to Identify and Evaluate New Opportunities. Minerals, 15(10), 1018. https://doi.org/10.3390/min15101018

15. Shi, L., Li, H., Wang, N., Han, P., Shen, Z., Yu, C., Zhang, X., & Meng, X. (2025). Methods for Verifying the Relationship Between Weak Uranium Anomaly and Uranium-Rich Geological Bodies in the Covered Areas of the Erlian Basin, Inner Mongolia. Minerals, 15(10), 1013. https://doi.org/10.3390/min15101013

ISSN 3030-3907

16. Wilke, F. D. H., Okrostsvaridze, A., Bluashvili, D., & Gabrielashvili, R. (2025). Geochemistry and Th–U–Total Pb Chemical Ages of Late Variscan Uranium Mineralisation at Shkhara, Greater Caucasus. Minerals, 15(9), 960. https://doi.org/10.3390/min15090960
17. Li, H., Wu, Z., Wang, S., Wang, Y., Dong, C., Li, X., Zhang, Z., Li, H., Liu, W., & Li, B. (2025). Three-Dimensional Attribute Modeling and Deep Mineralization Prediction of Vein 171 in Linglong Gold Field, Jiaodong Peninsula, Eastern China. Minerals, 15(9), 909. https://doi.org/10.3390/min15090909
18. Kurmanseiit, M., Shayakhmetov, N., Aizhulov, D., Abdullayeva, B., & Tungatarova, M. (2025). Computational Approaches to Assess Flow Rate Efficiency During In Situ Recovery of Uranium: From Reactive Transport to Streamline- and Trajectory-Based Methods. Minerals, 15(8), 835. https://doi.org/10.3390/min15080835
19. Аликулов Шухрат Шарофович, Курбанов Машхур Амонович, Шарафутдинов Улугбек Зиятович, Ражаббоев Ибодулла Муродуллаевич, & Юлдашев Шохрух Шоназар Угли (2023). Исследования поведения кремнезема и органики в продуктивных растворах подземного выщелачивания урана и их влияния на процесс сорбции урана. Universum: технические науки, (2-4 (107)), 22-27.6.
20. Duff, M. C., Amrhein, C. Uranium(VI) adsorption on goethite: spectroscopic and surface complexation modeling studies. Geochimica et Cosmochimica Acta, 1996, Vol. 60, pp. 351–364.

ISSN 3030-3907