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Assessment of Radioecological Safety of Coals and Ash and Slag Waste

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Abstract. *The analysis of statistical data on the natural radioactivity of coals from various deposits was carried out. It was noted that natural radioactivity is mainly caused by the presence of radioactive nuclides of uranium, thorium and potassium in coals, the concentration of which varies significantly. Fossil coals of Kazakhstan are generally characterized as weakly radioactive ones. In conceptual terms, a brief radiogeochemical characteristic of coals is given in terms of various forms of radionuclides in the constituent parts of coal. The fact of significant concentration of radionuclides in combustion waste (ash, slag) is confirmed. Ash and slag waste and fly ash enriched with these radionuclides pose a potential hazard to the environment. Systematic monitoring of the radioecological safety of coals and ash and slag waste is required.*

Keywords: *coal, ash content, combustion waste, natural radioactive elements, radioecological safety, gamma spectrometric analysis, concentration of radionuclides in ash and slag waste.*

Introduction

The Republic of Kazakhstan is among the top ten largest coal producers in the world market, and ranks third in reserves and production among the CIS countries. According to well-known Russian geochemist Ya.E. Yudovich and his colleagues [1], the clarke (average) uranium content in coals is – 3.6 g/t, thorium for brown coals is 6.3 g/t, and for hard coals – 3.5 g/t. In general, Kazakhstan coals are slightly radioactive, with a below-clarke content of radionuclides in coal. Coals consumed at Kazakhstan heat power plants are distinguished by a significant variety of grades. The volume of coal supplies to heat power plants is 65.9 million tons; there are more than 100 heat power plants in Kazakhstan.

Unlike Kazakhstan, in economically developed countries, only high-quality standardized coals with a low ash content are used in electricity generation, which allows the use of standard designs and equipment, burners and furnaces at heat power plants, simplifies and reduces the cost of projects and operation. Standardization of fuel by humidity, sulfur, nitrogen, ash content allows solving environmental problems, in particular those associated with an increased ash content of coals [2]. In general, this problem is also relevant for Russia; many Russian scientists are studying this problem.

According to the world researchers [2-4], the content of radioactive elements in coal and ash of some deposits varies: brown coals in Turkey U^{238} – 0.21-64.0 g/t, Th^{232} – 0.29-8.5; on Australia U^{238} – 0.04-43.0 g / t, Th^{232} – 0.4-17.0; hard coals in Canada U^{238} – 0.07-7.5 g/t, Th^{232} – 0.3-11.0; lignites in Spain with U^{238} content up to 298 g/t; subbituminous coals U^{238} 6.1 g/t, Th^{232} – 5.6; USA U^{238} – 1.06-40.4 g/t, Th^{232} – 0.89-4.4; in Siberian region of Russia U^{238} – 2.0, Th^{232} – 2.4; in Far East of Russia U^{238} – 1.7 g/t, Th^{232} – 4.2; in Kazakhstan U^{238} – 1.8 g/t, Th^{232} – 2.2 g/t; in Mongolia U^{238} – 2.7 g/t, Th^{232} – 3.6; in Iran U^{238} – 2.2 g/t, Th^{232} – 5.7 g/t.

Table 1 presents the data of coal radioactivity of some world deposits [5].

Although coals of Kazakhstan are slightly radioactive, some deposits have an increased uranium content in coals, for example, in weathered coals of the Shubarkol deposit, ura-

Table 1 – RE content in coals of some world deposits [5]

Country	U^{238}	Th^{232}	K^{40}	Ra^{226}
Countries of the former USSR	28	25	120	-
USA	18	21	52	22
	1-540	2-320	1-710	
China	7	16	30	
Germany	-	-	-	26
Poland	-	-	-	2-35
Great Britain	14,2	12,6	166	14,9
	7,8-30	7-19,2	55-314	8,9-25,5
Czechoslovakia	-	-	-	4-13
Eastern Donbass anthracite culm	76	21	300	34
Chita region.Urtuisky deposit	100-12300	24-800	2,5-780	

Note. The numerator contains the average values of the ERN contents; the denominator contains the limits of variation of these values.

nium concentrations exceed 1000 g/t, which leads to the need for special disposal or decontamination of weathered coals [6].

Coals containing uranium in concentrations one to two orders of magnitude higher than the clarke are known in many countries of the world: in Russia, Kyrgyzstan, Turkey, France, the USA and other countries. The specific activity of NRN in coals of different deposits differs by 100¸1000 times or more (for example, the activity of U^{238} varies within 0.6...3600 Bq/kg with an average content of 18...28 Bq/kg) [7]. In general, in coals around the world, the average specific activity in U^{238} and Th^{232} coals is estimated at 20 Bq/ g, and K^{40} – 50 Bq/kg. In the presence of uranium anomalies in areas of coal deposits, variations in the specific activity of NRN are 3.6-8.4*10^4 Bq/kg.

According to American experts [8], the total global emission of uranium and thorium as a result of coal combustion is about 37,300 tons annually, with about 7,300 tons coming from the United States.

According to experts, «if the average radioactivity of Ra^{226} in the burned coal exceeds 100 Bq/kg, and Th^{228} 150 Bq/kg, then the resulting ash should be subject to radiometric control, and if the limit for total alpha activity established by sanitary rules, equal to 7 kBq/kg, is exceeded, it should be considered radioactive waste and sent for disposal» [9].

In the course of exploitation of coal deposits, a large amount of coal and coal-bearing rocks containing radioactive elements comes to the surface. During the combustion and use of coal at heat power plants, radioactive and the other elements pass into ash dumps, some into fly ash emitted from the pipes of heat power plants, thereby polluting water, soil and the atmosphere. It is also necessary to pay special attention to studying the territories around heat power plants, since large volumes of ash and slag containing radioactive elements, pollute the surface of the earth for many kilometers. This happens due to the precipitation of fly ash that contains high concentrations of radioactive elements. According to the International Atomic Energy Agency, the global total emission of uranium and thorium from coal combustion is about 37.3 tons annually [7].

The uranium content in slag remains approximately the same as in the associated rocks. Fly ash can contain a large amount of NRN. In [9], based on the analysis of domestic publications, it is stated that even when burning coals with a low content of radioactive elements in the products of their combustion, the content of uranium and thorium in fly ash increases 3-4 times, and sometimes 9 times in relation to the original fuel.

A number of researchers, on the contrary, believe that the main source of radioactive pollution of the environment when burning coals with an increased content of radioactive elements is the finely dispersed component of ash: fly ash that is practically not captured by the electrostatic precipitators of heat power plants [10].

In the context of the global trend towards sustainable development, there is a problem of recycling ash and slag waste from heat power plants. The use of this waste in the construction industry is of particular importance due to the resource intensity of the production of building materials. Fly ash in building materials can significantly affect the natural radioactivity of structures and increase the radiation background in buildings. This is due to the fact that when coal is burned, fly ash is enriched with natural radionuclides. The largest consumer of solid fuel combustion waste is the production of building materials, which uses a huge amount of natural resources [11].

Based on the above, it can be said that the processes of coal combustion and ASW utilization are a pressing issue that receives little attention [12]; in this regard, the task is to study radioactivity of coals and ASW in the context of their impact on the environment.

Research methods

In the course of the work, new data of the radioactivity of Ekibastuz coals and some samples of the Karaganda basin and the Molodezhny open pit were obtained. In total, the results are presented for 5 coal samples and 5 coal ash samples. The sampling was carried out by taking samples of stored coal for testing for the content of radioactive elements in them using the gamma spectrometry method with a semiconductor detector in the laboratory of the Ecoexpert LLC.

Results and discussion

Currently, many works have been published that study metal concentrations in coals and coal ash and consider their industrial concentrations. This topic is especially relevant for countries with a high level of coal production and large coal resources, such as China, Russia, the USA, Australia and others. The geochemistry of coals in Kazakhstan has been poorly studied; studying trace elements in coals has begun to be carried out relatively recently.

Work [3] provides some data on studying radioactive elements in coals and coal ash of some countries, including Kazakhstan. For Karaganda coal of the Carboniferous age, the content of U is 0.6 g/t, Th – .1 g/t; for ash U – 6.1 g/t, Th – 11.2 g/t; for the Ekibastuz basin coal U – 1.1 g/t, Th – 3.1 g/t; for ash U – 3.0 g/t, Th – 8.6 g/t. For the Jurassic coals of the Karazhyra deposit (7 samples) the content of U is 0.5 g/t, Th – 1.0 g/t; for ash U – 4.3 g/t, Th – 8.5 g/t; the Maikube basin coal U – 5.0 g/t, Th – 3.6 g/t; for ash U – 19.6 g/t, Th – 14.1 g/t. For Mongolian coals of the Carboniferous age, the average uranium content in coal is 1.4 g/t, thorium 3.1 g/t; for coal ash U – 9.5 g/t, Th – 21.1 g/t. For the Jurassic coals the average content of U – 2.7 g/t, Th – 3.6 g/t; for coal ash U – 16.7 g/t, Th – 22.1 g/t.

From these data it is seen that the conclusions on the content of radioactive elements in Kazakhstan coals were made based on a relatively small number of samples, which once again proves the need for high-quality studying and monitoring of the radioactivity of coals in the Kazakhstan deposit.

In general, in coals of the same age, the concentration of uranium and thorium is similar on average, because the elements in coals mostly accumulate during the process of coal formation. In this regard, studying the forms of natural radioactive elements, in particular uranium in coals, is of great importance for determining the conditions of coal formation for different models of element behavior, when burning coal at heat power plants and for linking the technologies of complex processing of coal and ash and slag waste.

Serious environment safety problems are associated with solid waste from heat power plants (ash and slag). When coal is burned, its organic part burns forming flue gases, and the inorganic part forms ash and slag. Therefore, most of the impurities in the process of coal combustion pass into fly ash, as it can also accumulate a potentially dangerous concentration of toxic and radioactive elements that are carried into the atmosphere together with flue gases; thereby pollutants are dispersed over a wide area, which has a significant toxic effect on the environment. There is evidence that when burning coal at heat power plants, the concentration of radionuclides in slag and ash is 10 times higher than in coal [2].

In coals with abnormal uranium content, there predominates the dispersed form of occurrence, its uneven distribution, but the main mass is concentrated in the form of accumulations in organic matter. In the process of changing the structure of organic matter, the ratio of uranium occurrence forms changes, while the role of its occurrence in the mineral part of the matter increases. A fairly long period of studying the forms of U occurrence in coals has established only the idea of its connection with organic matter [13].

Using the example of various deposits in Northern Asia, it has been shown that dispersed forms of uranium occurrence predominate in brown peat and hard coals, along with the dispersed form associated with organic matter, mineral forms represented by uraninites, coffinite and minerals in which uranium is included as an isomorphic impurity (zircon, xenotime and others) have been established [14].

Due to the absence of demand in industry, the geochemistry of thorium has been poorly studied, since abnormally high concentrations of thorium in coal are rare. However, studies conducted in recent years have shown that when coal is burned at heat power plants, a significant proportion of thorium is released into the atmosphere with flue gases and can have a significant impact on the environment. The concentration of thorium in flue gases depends on the thermochemical stability of the organic and mineral components of coal: thorium carriers [15]. The geochemistry of radium is largely determined by the features of uranium migration and concentration, as well as the chemical properties of radium itself.

Our studies of coal and coal ash have shown that the concentration of natural radionuclides in coal ash exceeds the concentration in coal by 3-5 times (Table 2). Attention should be paid to monitoring ash and slag waste and dumps, since ash dumps occupy vast territories, and in fact form quasi-anthropogenic deposits of natural radionuclides.

The results of the study show that the Ekibastuz coals have a near-clarke content of natural radioactive elements, while the thorium and radium contents in coal and ash from the Molodezhny open-pit coal exceed the clarke content.

The Th concentration in the Ekibastuz coals was 11.7-13.0 Bq/kg, which is a near-clarke content, while the thorium content in coal and ash from the Molodezhny open-pit coal slightly exceeds the clarke value, 26.0 Bq/kg and 94.0 Bq/kg, respectively.

The concentration of K^{40} in the coal of the Ekibastuz basin is within 47.0-136.0 Bq/kg, in ash 170.0-270.0 Bq/kg. In the coal of the Karaganda basin, the K^{40} content is 39.0 Bq/kg, in ash – 220.0 Bq/kg; in coal of the Molodezhny open-pit mine K^{40} is 34.0 Bq/kg, in ash – 240.0 Bq/kg.

As the ratio of the specific activity of the nuclide in ash and coal, which depends on the completeness of coal ashing, grade composition and its ash content, the concentration factors were calculated: K_{Ra} – 3.7-4.7; K_{Th} – 3.6-6.5; K_{K}^{40} – 4.0-8.6.

Based on the obtained results, it is seen that Ekibastuz and Karaganda coals are slightly radioactive; for a more accurate assessment and prediction of environmental pollution, it is necessary to conduct a study of not only coal and solid ash samples but also to study a multi-kilometer area around the heat power plant due to the NRN spread in the atmospheric air emitted with fly ash from the pipes of the heat power plant and deposited on the earth's surface. Despite the obviousness of the problem of radiochemical and radiological studies, this problem is solved relatively poorly. In this regard, it is necessary to pay due attention to studying radioactivity in coals and coal ash, since they can be potentially dangerous.

To understand the nature of the radioactive elements accumulation and distribution in combustion waste, it is necessary to study radiogeochemical characteristics of coals. This issue is important for study, since the form of radionuclide presence gives some understanding of what part of the elements remains in the solid phase of ash, and what part evaporates with flue gases into the atmosphere polluting the environment.

Table 2 – Results of studying coal and coal ash using the gamma spectrometry method, Bq/kg

Deposit	Name	Ad, %	Actual indicators, Bq/kg			Concentrating coefficients		
			Ra^{226}	Th^{232}	K^{40}	Ra	Th	K^{40}
Ekibastuz	**Ash T-2**		**53**	**50**	**170**	4,73	3,85	4,05
	Coal T-2	32,8	11,2	13	<42			
	Ash-T12		**60**	**67**	**240**	4,72	5,73	8,57
	Coal T-12	37,2	12,7	11,7	<28			
	Ash T-18		**70**	**65**	**270**	4,7	5,04	4,28
	Coal T-18	38,2	14,9	12,9	63			
Karaganda CB	**Ash K-2**		**82**	**84**	**220**	3,72	6,46	5,64
	Coal K-2	35,0	22	13	39			
Molodezhny	**Ash Topar**		**140**	**94**	**240**	3,78	3,61	7,06
	Coal Topar	39,9	37	26	34			
Clarke in coal*			1,9	3,2				
Clarke in ash*			15	23				

Note. * – according to Ketris, Yudovich, 2009

Conclusions

The presence of natural radioactive elements in coals and their concentration in combustion waste suggest radioecological monitoring of the radioactivity level in burned coals and ash and slag waste in the areas of deployment of coal mining and processing enterprises. It is necessary to continue studies to clarify the radiogeochemical features of the radioactive nuclides distribution in coals with a variable ash content and different degrees of metamorphism.

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REFERENCES

1. Yudovich Ya.E., Ketris M.P., Merts A.V. Trace elements in fossil coals. L: Nauka, 1985. 239 p.
2. Sidorova G.P., Krylov D.A., Ovcharenko N.V. Radiation situation in the areas of coal-fired heat power plants in Russia. Bulletin of ZabCU. 2017. Vol. 23. No. 5. Pp. 36-44.
3. Arbuzov S.I., Volostnov A.V., Mashenkin V.S., Rybalko V.I. Radioactive elements (U, Th) in coals. Proceedings of the IV International Conference, Tomsk. 2013. Pp. 56-62.
4. Bouska V. Int. J. Coal Geol. – 1999. V. 40. No. 2-3. P. 211.
5. Shpirt M.Ya., Rashevsky V.V. Forms of compounds and behavior of trace elements in the processing of fossil fuels. M.: Kuchkovo pole, 2010. 384 p.
6. Amangeldykyzy A. Study of the prevalence of rare earth metals in coals of the main coal basins of Central Kazakhstan: PhD dis.: 6D070600. Karaganda, 2021. 202 p.
7. Davydov M.G., Timonina Yu.A. Radiation situation in the area of the state district power plant of the Rostov region. Heat power engineering. 2003. No. 12. Pp. 8-13.
8. Richard Rhodes, Denis Beller. The need for nuclear energy. A Look at the World's Difficult Energy Future. IAEA Bulletin. 2000. V. 42. No. 2. Pp. 43-50. (42/2/2000 – June 2000). Vienna. Austria.
9. Nazirov R., Vede P., Tarasov I., Zhuikov A., Sergunicheva E., Tolochko O. Distribution of natural radionuclides in ashes, collected by heat power plants electrostatic precipitator. Bulletin of Tomsk Polytechnic University. Geo Assets Engineering. 2023. V. 334. 7. Pp. 177-186.
10. Ovseychuk V.A., Krylov D.A., Sidorova G.P. Radiation emissions from coal-fired heat power plants. Bulletin of the Transbaikal State University. 2012. No. 10. Pp. 24-29.
11. ACAA. Coal Ash Recycling Rate Increases in 2020, Reversing Declines in Previous Two Years. 2021. URL: https://acaausa.org/ (date of access 08/29/2024).
12. Pak Yu., Pak D., Nuguzhinov Zh., Tebayeva A. Natural radioactivity of coal in the context of radioecological safety and rational use. News of Universities. Mining Journal. 2021. No. 1. Pp. 97-106. DOI: 10.21440/0536-1028-2021-1-97-106
13. Arbuzov S.I., Ilyenok S.S., Volostnov A.V., Maslov S.G., Arkhipov V.S. Forms of uranium occurrence in coals and peat of Northern Asia. Bulletin of Tomsk Polytechnic University. 2011. V. 319. No. 1. Pp. 109-115.
14. Ren W., Cao Q., Yang L., Huang S. Uranium in Chinese coals: Concentration, spatial distribution, and modes of occurrence. Journal of Environmental Radioactivity. 2022. V. 246. 106-848. URL: https://doi.org/10.1016/j.jenvrad.2022.106848
15. Arbuzov S.I., Volostnov A.V. Forms of thorium concentration in coals. Bulletin of Tomsk Polytechnic University. 2003. V. 306. No. 6. Pp. 12-17.

Көмір және күл-шлак қалдықтарының радиоэкологиялық қауіпсіздігін бағалау

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***Аңдатпа.** Әртүрлі кен орындарындағы көмірлердің табиғи радиоактивтілігі туралы статистикалық мәліметтерге талдау жүргізілді. Табиғи радиоактивтілік негізінен көмірлерде уранның, торийдің және калийдің радиоактивті нуклидтерінің болуымен түсіндіріледі, олардың концентрациясы айтарлықтай шектерде өзгереді. Қазақстанның қазбалы көмірлері әдетте әлсіз радиоактивті болып сипатталады. Тұжырымдама бойынша көмірдің қысқаша радиогеохимиялық сипаттамасы көмірдің құрамдас бөліктерінде радионуклидтердің пайда болуының әртүрлі формалары тұрғысынан берілген. Жану қалдықтарында (күл, шлак) радионуклидтердің айтарлықтай шоғырлану фактісі расталды. Осы радионуклидтермен байытылған күл-шлак қалдықтар және ұшатын күл қоршаған ортаға ықтимал қауіп төндіреді. Көмір мен күл қалдықтарының радиоэкологиялық қауіпсіздігіне жүйелі мониторинг жүргізу қажет.*

***Кілт сөздер:** көмір, күл, жану қалдықтары, табиғи радиоактивті элементтер, радиоэкологиялық қауіпсіздік, гамма-спектрометриялық талдау, күл-шлак қалдықтарындағы радионуклидтердің концентрациясы.*

Оценка радиоэкологической безопасности углей и золошлаковых отходов

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***Аннотация.** Проведён анализ статистических данных о естественной радиоактивности углей различных месторождений. Отмечено, что природная радиоактивность в основном обусловлена наличием в углях радиоактивных нуклидов урана, тория и калия, концентрация которых меняется в значительных пределах. Ископаемые угли Казахстана в целом характеризуются как слаборадиоактивные. В концептуальном плане дана краткая радиогеохимическая характеристика углей с точки зрения различных форм нахождения радионуклидов в составных частях угля. Подтверждается факт существенного концентрирования радионуклидов в отходах сжигания (зола, шлак). Золошлаковые отходы и летучая зола, обогащенные указанными радионуклидами, представляют потенциальную опасность для окружающей среды. Необходим системный мониторинг радиоэкологической безопасности углей и золошлаковых отходов.*

***Ключевые слова:** уголь, зольность, отходы сжигания, природные радиоактивные элементы, радиоэкологическая безопасность, гамма-спектрометрический анализ, концентрирование радионуклидов в золошлаковых отходах.*

REFERENCES

1. Yudovich Ya.E., Ketris M.P., Merts A.V. Trace elements in fossil coals. L: Nauka, 1985. 239 p.
2. Sidorova G.P., Krylov D.A., Ovcharenko N.V. Radiation situation in the areas of coal-fired heat power plants in Russia. Bulletin of ZabCU. 2017. Vol. 23. No. 5. Pp. 36-44.
3. Arbuzov S.I., Volostnov A.V., Mashenkin V.S., Rybalko V.I. Radioactive elements (U, Th) in coals. Proceedings of the IV International Conference, Tomsk. 2013. Pp. 56-62.
4. Bouska V. Int. J. Coal Geol. – 1999. V. 40. No. 2-3. P. 211.
5. Shpirt M.Ya., Rashevsky V.V. Forms of compounds and behavior of trace elements in the processing of fossil fuels. M.: Kuchkovo pole, 2010. 384 p.
6. Amangeldykyzy A. Study of the prevalence of rare earth metals in coals of the main coal basins of Central Kazakhstan: PhD dis.: 6D070600. Karaganda, 2021. 202 p.
7. Davydov M.G., Timonina Yu.A. Radiation situation in the area of the state district power plant of the Rostov region. Heat power engineering. 2003. No. 12. Pp. 8-13.
8. Richard Rhodes, Denis Beller. The need for nuclear energy. A Look at the World's Difficult Energy Future. IAEA Bulletin. 2000. V. 42. No. 2. Pp. 43-50. (42/2/2000 – June 2000). Vienna. Austria.
9. Nazirov R., Vede P., Tarasov I., Zhuikov A., Sergunicheva E., Tolochko O. Distribution of natural radionuclides in ashes, collected by heat power plants electrostatic precipitator. Bulletin of Tomsk Polytechnic University. Geo Assets Engineering. 2023. V. 334. 7. Pp. 177-186.
10. Ovseychuk V.A., Krylov D.A., Sidorova G.P. Radiation emissions from coal-fired heat power plants. Bulletin of the Transbaikal State University. 2012. No. 10. Pp. 24-29.
11. ACAA. Coal Ash Recycling Rate Increases in 2020, Reversing Declines in Previous Two Years. 2021. URL: https://acaausa.org/ (date of access 08/29/2024).
12. Pak Yu., Pak D., Nuguzhinov Zh., Tebayeva A. Natural radioactivity of coal in the context of radioecological safety and rational use. News of Universities. Mining Journal. 2021. No. 1. Pp. 97-106. DOI: 10.21440/0536-1028-2021-1-97-106
13. Arbuzov S.I., Ilyenok S.S., Volostnov A.V., Maslov S.G., Arkhipov V.S. Forms of uranium occurrence in coals and peat of Northern Asia. Bulletin of Tomsk Polytechnic University. 2011. V. 319. No. 1. Pp. 109-115.
14. Ren W., Cao Q., Yang L., Huang S. Uranium in Chinese coals: Concentration, spatial distribution, and modes of occurrence. Journal of Environmental Radioactivity. 2022. V. 246. 106-848. URL: https://doi.org/10.1016/j.jenvrad.2022.106848
15. Arbuzov S.I., Volostnov A.V. Forms of thorium concentration in coals. Bulletin of Tomsk Polytechnic University. 2003. V. 306. No. 6. Pp. 12-17.