MINING SCIENCE AND TECHNOLOGY (RUSSIA)
ГОРНЫЕ НАУКИ И ТЕХНОЛОГИИ
eISSN 2500-0632
https://mst.misis.ru/

BENEFICIATION AND PROCESSING OF NATURAL AND TECHNOGENIC RAW MATERIALS

Research paper

https://doi.org/10.17073/2500-0632-2023-05-116
UDC 622

Assessing viability of processing ash and slag dumps for energy-efficient ash beneficiation at Magadan CPP

L. V. Shipunov[1], **M. A. Kuzmenkov**[1], **N. K. Gaidai**[1,2] ✉
[1] *North-Eastern State University, Magadan, Russian Federation*
[2] *North-Eastern Integrated Research Institute named after N.A. Shilo of Far Eastern Branch of the Russian Academy of Sciences, Magadan, Russian Federation*
✉ *nataly_mag@rambler.ru*

Abstract
Complex processing of ash and slag waste is a supported directions for the development of environmental friendliness and performance in power engineering. The rational use of this waste in large-scale production processes has now been realized in the construction field. The development of up-to-date beneficiation technologies raises the possibility of extracting various useful components from ash and slag wastes. This study aims to investigate the potential for using energy-efficient ash beneficiation to produce a heavy metal-containing fraction and separate the magnetic fraction. To assess the feasibility of ash beneficiation and its rational use, the technical documentation of ash and slag dumps of PJSC "Magadanenergo" was studied, and semi-quantitative analyses of samples collected from these dumps were carried out. The data on the content of useful components and quantities of ash and slag enabled us to develop complex beneficiation flow sheets, assess their process efficiency, and evaluate their potential financial viability. The estimated volume of metals to be recovered includes 785 tons of Ti (me-1), 183 tons of Sr (me-2), and 4,867 tons of Fe (me-3). The performance indicators of the beneficiation and aggregated values of economic indicators for this project implementation on an industrial scale were calculated. The economic feasibility of the ash processing project showed good values for two out of three models over a ten-year planning horizon. Implementing the project also effectively improves the environmental situation by potentially processing up to 10% of the total volume of ash dumps, fulfilling one-fifth of the Energy Strategy of the Russian Federation's requirements until 2035. While investigations of ash from the Magadan Cogeneration Power Plant (MCPP) are not new, they were not previously carried out within the framework of studying integrated processing of ash to obtain various useful components.

Keywords
ash, Magadan Cogeneration Power Plant, waste, beneficiation, samples, cost efficiency, ecology, Magadan

For citation
Shipunov L. V., Kuzmenkov M. A., Gaidai N. K. Assessing viability of processing ash and slag dumps for energy-efficient ash beneficiation at Magadan CPP. *Mining Science and Technology* (*Russia*). 2024;9(1):12–20. https://doi.org/10.17073/2500-0632-2023-05-116

ОБОГАЩЕНИЕ, ПЕРЕРАБОТКА МИНЕРАЛЬНОГО И ТЕХНОГЕННОГО СЫРЬЯ

Научная статья

Оценка целесообразности переработки золошлаковых отвалов Магаданской теплоэлектроцентрали

Л. В. Шипунов[1], **М. А. Кузьменков**[1], **Н. К. Гайдай**[1,2] ✉
[1] *Северо-Восточный государственный университет, г. Магадан, Российская Федерация*
[2] *Северо-Восточный комплексный научно-исследовательский институт им. Н.А. Шило Дальневосточного отделения Российской академии наук, г. Магадан, Российская Федерация*
✉ *nataly_mag@rambler.ru*

Аннотация
Комплексная переработка золошлаковых отходов является одним из поддержанных направлений развитий экологичности и эффективности производства энергетики. Рациональное использование их в массовом производстве в настоящее время реализовано в области строительства. Развитие современных технологий обогащения позволяет ставить вопрос о получении из золошлаковых отхо-

дов различных полезных компонентов. Цель данного исследования – изучение возможности применения энергоэффективного обогащения золы с целью производства тяжелой металлосодержащей фракции и отделения магнитной фракции. Для оценки возможности обогащения золы и ее рационального использования была исследована техническая документация золошлаковых отвалов ПАО «Магаданэнерго» и проведены полуколичественные анализы отобранных проб с золошлакового отвала. Полученные данные по содержаниям полезных компонентов и количеству золошлаков позволили разработать комплексные обогатительные схемы с оценкой их технологической эффективности и произвести оценку потенциальной экономической эффективности. Объем металлов, планируемых к извлечению, по оценкам, составил: для Ti(me-1) – 785 т, для Sr(me-2) – 183 т и для Fe(me-3) – 4867 т. Рассчитаны технологические показатели обогащения и укрупненные значения экономических показателей для реализации данного проекта в промышленных масштабах. Экономическая целесообразность проекта по переработке золы в двух моделях из трех показывает хорошие значения в десятилетнем горизонте. Реализация проекта эффективна и с точки зрения улучшения экологической ситуации, т.к. позволяет вовлечь в переработку до 10 % всего объема золоотвалов, что на пятую часть выполняет требования Энергетической стратегии Российской Федерации до 2035 года. Исследования золы Магаданской теплоэлектроцентрали (МТЭЦ) не являются новыми, но в рамках исследования комплексной переработки золы с целью получения различных полезных компонентов ранее работы не проводились.

Ключевые слова
зола, МТЭЦ, отходы, обогащение, пробы, экономическая эффективность, экология, Магадан

Для цитирования
Shipunov L.V., Kuzmenkov M.A., Gaidai N.K. Assessing viability of processing ash and slag dumps for energy-efficient ash beneficiation at Magadan CPP. *Mining Science and Technology* (*Russia*). 2024;9(1):12–20. https://doi.org/10.17073/2500-0632-2023-05-116

Introduction

Ash and slag waste has plagued mankind since the industrial revolution, posing significant environmental challenges. The complex processing of ash and slag waste is recognized as a vital approach to enhancing the environmental friendliness and efficiency of power engineering[1].

So far, the rational use of such waste in large-scale production has been limited to various construction processes [1–3]. However, the development of up-to-date beneficiation technologies has opened up opportunities to explore new sources of minerals. One such research avenue is the beneficiation of ash to extract valuable components, including precious and rare metals, underburnt coal, and the potential for producing sorbent [4]. Numerous studies have focused on recovering magnetite [5, 6], precious and rare metals [7–9], and aluminosilicates [10, 11]. The economic outcomes of these projects have varied across different periods of the Russian market's development, with profitability largely depending on the success in marketing the extracted products.

To date, no extensive research has been conducted on processing ash and slag waste for the purpose of extracting titanium concentrate, nor has the economic efficiency of such projects been assessed. This gap may be attributed to the challenges associated with the material composition of ash and underburnt coal pellets. The effectiveness of beneficiation varies significantly with the composition and ratio of these materials.

The authors have previously studied and reported on the compositions and types of coals supplied to the MCPP over the last 20 years [12]. Briefly, the coal from the Talda deposit (Kuzbass) is characterized as a typical long-flame steam low-ash coal, rich in limestone within the mineral particles. Coals from different mining areas of the deposit were washed together, resulting in a final blended fraction delivered to MCPP.

Annually, PJSC Magadanenergo supplies about 300 000 tons of coal from the aforementioned deposit (Kemerovo coal basin, Kuzbass)[2]. Concurrently, during the autumn-spring heating season and the maintenance of boiler units in the summer, about 33 000 m^3 of ash and slag waste are generated. With a density of 1.2–1.3 t/m^3, this amounts to about 41 000 t of ash and slag waste per year.

Problem definition

To date, there is no cost-effective, proven technology for processing ash and slag wastes from the Magadan Cogeneration Power Plant (MCPP), as required by the Energy Strategy of the Russian Federation.

[1] "Round table" on the topic "Legislative regulation" regulation of the use of ash and slag waste from coal TPP". Ministry of Energy of the Russian Federation. URL: https://minenergo.gov.ru/node/140114 (accessed date: 20.11.22).

[2] Batakova O.G. Magadanenergo will bring more than 300 kt of coal for the heating season of 2021–2022. Website of PJSC Magadanenergo. 2021; URL: http://www.magadanenergo.ru/content/magadanenergo-zavezet-bolee-300-tysyach-tonn-uglya-dlya-otopitelnogo-sezona-2021-2022 (accessed date: 03.05.2021).

Studies on the use of MCPP ash as a component of clinkers in cement mixtures for concrete production have proved unsuccessful due to the high content of calcium oxide, which adversely affects the strength properties of the resulting concrete. The grade of the concrete decreases from B30 to B10, which is unacceptable for the construction of critical buildings and structures of the energy industry. Meanwhile, research on the application of ash and slag wastes in small-scale construction products (bricks, blocks, plates) has not been in demand due to the limited volume of residential construction in Magadan from 2010 to 2022.

On the other hand, the Energy Strategy of the Russian Federation for the period up to 2035 requires all energy companies using coal in their energy generation to develop measures to reduce the environmental impact on the areas where thermal power plants are located, including taking into account the involvement of ash and slag waste in processing. According to this strategy's provisions, 15% of all generated ash and slag waste should be utilized and neutralized by 2024, and 50% by 2035[3].

Based on our previous studies and the studies of other authors in similar areas, we have focused on the ash and slag dumps of MCPP with the aim of obtaining a heavy fraction (extremely saturated with various metal oxides, such as those of titanium, zirconium, strontium, rubidium, and sulfides of zinc and copper), which could be subsequently processed by various methods to obtain metal concentrates. For titanium and zirconium oxides, we intended to apply a technique of alternating magnetic and electric separation with a successive increase in the magnetic field induction of separators, aiming to obtain a separate magnetic concentrate with a grade of about 53–62 wt. % (as indicated by preliminary studies), and selective concentrates of ilmenite, rutile, monazite, and zircon. For the extraction of strontium and rubidium, we propose to use a sequential scheme of electric separators with final acidic dissolution and concentrate separation in an electrolysis unit.

Research techniques

The primary objective of this work is to study the yield of the heavy fraction from ash and slag waste by applying traditional methods of gravity, magnetic, and electric beneficiation, as well as to calculate the economic feasibility of this process. The expected metal concentrates comprising the heavy fraction from the initial gravity beneficiation, which are considered in further calculations, are listed as previously mentioned.

To achieve this goal, the following tasks were undertaken:

1) *Estimation of ash volumes accumulated in the ash and slag dumps of MCPP*. This analysis was performed by processing and compiling the statistical information provided by MCPP along with field observations of the ash and slag waste generation and storage processes, including pouring into the ash dump [13].

2) *Sampling and semi-quantitative analysis of useful components in the ash and slag wastes of MCPP*. This analysis was performed using the energy-dispersive X-ray fluorescent spectrometer EDX-800HS2 manufactured by “Shimadzu” (Japan), utilizing semi-quantitative of energy-dispersive X-ray fluorescent spectroscopy method. Measurement conditions were as follows: Rh anode tube (50-watt power), voltage settings of 50 kV and 15 kV, a current of 100 μA (auto), in a helium medium, with a measurement diameter of 5 mm and a measurement time of 100 s. The samples were measured in the Ti-U (0.00–40.00 keV), Na-Sc (0.00–4.40 keV), and S-K (2.1–3.4 keV) bands [13].

The samples were collected at MCPP's ash and slag dump, located near Rechnaya Street. The sampling technique involved first identifying the main zones of the ash disposal area (dump): the safety berm, hydrotransport outflow zones, ash mixing zones, net ash hydraulic deposition zones. Samples were taken from the net ash hydraulic deposition zones at a depth of about four meters, after removing the overlaying layers of ash and slag waste, which were then moved to another dump by PJSC “Magadanenergo” machinery according to the schedule of ash and slag relocation. The samples were taken along the flank using the handful method. Approximately eight handfuls of material, each weighing just over 1 kg, constituted one flank sample. These samples were subsequently mixed in the mineral processing laboratory of SVSU Polytechnic Institute using the coning and quartering method three times, then dried and quartered mechanically at a classical splitter. One-eighth of the sample was sent for semi-quantitative analysis [13]. In total, eight flank samples were collected, amounting to 72.4 kg of initial ash before drying. The weight of the samples decreased to 58.2 kg after drying.

3) *Development and basic calculation of rational beneficiation process flow sheets*. The development of the flow sheets was based on the classical flow sheets for the beneficiation of titanium-zirconium sands from alluvial deposits, with subsequent

[3] Energy Strategy of the Russian Federation for the period up to 2035. Ministry of Energy of the Russian Federation; 2020. URL: https://minenergo.gov.ru/node/1026 (accessed date: 20.11.22).

magnetic-electric concentration on the appropriate separators. The recovery of strontium was also calculated [14]. The flow sheets took into account the equipment fleet in the SVSU beneficiation laboratory, which consists mainly of gravity beneficiation units (high-frequency jigging machine MOL2.5, concentration tables SKO-1 and RP-4, screw separator, fine filling sluice with rubber high-profile stencil, centrifugal separator) and magnetic and electric beneficiation units (drum-type magnetic separator, liquid magnetic separator, dry high-gradient field magnetic separator, drum-type electric separator). The classical method of beneficiation theory calculation was used: product yields and recoveries were calculated from the grades in the feed, concentrate, and tailings. From the yields and recoveries, the expected concentrate volumes were calculated [15].

4) *Calculation of basic economic indicators for the selected process flow sheets to determine feasibility of further development of the ash processing project*. Economic indicators were calculated using the refined NPV method as outlined by Atkinson, 2005 [16]. The basic rigid model was built based on these calculations, and additional scenarios were defined according to it: pessimistic, realistic, and optimistic (each of which took into account the possibilities of achieving the preset values of productivity, recovery, and sale of marketable products at the preset prices, according to the scenarios).

Research Findings

The ash volumes were obtained by processing the total dataset of field observations, which took the form of statistical information on the ash dumps of MCPP, provided by PJSC "Magadanenergo". The main values used in further calculations are summarized in Table 1. Maps of the dumps and the sampling locations have been given in the previously published materials by the authors [17].

Semi-quantitative analyses of the ash composition were conducted on samples collected in July 2022 using the method described above to estimate the quantities of metals in the MCPP ash. Sampling was performed on the flanks of the net ash hydraulic deposition zones to reduce the probability of sample contamination by surrounding rocks [13, 14].

The semi-quantitative analyses of the ash composition were carried out by the specialists from the Institute of Organic and Physical Chemistry named after A. E. Arbuzov, which is a separate structural subdivision of the FITs Kazan Scientific Center of RAS. The determined percentages of components in MCPP ash are summarized in Table 2.

Mineralogical studies showed that the composition of the samples corresponds to the typical composition of ash and slag waste. They contain quartz, silicates, iron oxides, pyrite, carbonate, silicon, pyrrhotite, pure iron, brass (Cu + Zn), as well as iron alloys of various compositions: Fe-Ni-Cr alloy, ferrochromite (Cr + Fe), and iron with chromium and manganese (Fe + Cr and Fe + Mn with manganese content up to 0.78%), celestine, and traces of carnallite.

The main operational parameters established in the course of the analysis of rational beneficiation flow sheets were calculated by analogy with similar projects for the processing of alluvial titanium-zirconium deposits material [15], and for magnetite, based on the studies of L. N. Adeeva and V. F. Borbat [18].

Table 1

Brief technical characteristics of ash dumps at MCPP

Designation	1 quarter of 2021	2 quarter of 2021	3 quarter of 2021	4 quarter of 2021
Total disposal, thousand m3 (by quarter)	13.38	3.50	1.94	11.25
ZShO-1*, section 1	13.38	0.00	0.00	0.00
ZShO-1, section 2	0.00	3.50	1.94	11.25
Accumulated total at ZShO-1, thousand m^3	2,713.20	2,704.70	2,706.70	2,708.10
Accumulated total at ZShO-1, kt	3,255.90	3,245.70	3,248.10	3,249.70
Accumulated total at section 1 of ZShO-1, thousand m^3	2,108.50	2,111.50	2,111.50	2,101.70
Accumulated total at section 2 of ZShO-1, thousand m^3	604.70	593.30	595.20	606.50
Accumulated total at ZShO-2**, thousand m^3	1,781.80	1,796.80	1,796.80	1,806.60
Accumulated total at ZShO-2, kt	2,138.10	2,156.10	2,156.10	2,167.90

* ZShO-1 is ash and slag dump 1, located in the immediate vicinity of Rechnaya Street near Pionerny and Solnechny urban districts.

** ZShO-2 is ash-and-slag dump 2, located over a distance from Rechnaya Street, in the valley of the Balakhapchan River, is connected by a dirt road with ash-and-slag dump 1.

eISSN 2500-0632
https://mst.misis.ru/

The operational parameters of the MCPP ash-and-slag waste beneficiation, as calculated [19], are given in Table 3. The initial percentages were taken to be equal to the median average values from Table 2 for the corresponding components.

Based on the values obtained according to formula 1, the quantities of useful components (metals to be extracted) were calculated:

$$V_{Me} = V_{ZShO-1} \cdot a_{Me}, \quad (1)$$

where V_{Me} is the calculated metal quantity, t, V_{ZSho-1} is the ash dump volume, t, and a_{Me} is the initial metal percentage.

From the total metal quantities obtained, the extractable quantity is determined, taking into account process losses. To account for losses, a correction coefficient $K_{ben.}$ was introduced, which took into account the total losses (its value ranges from 0.75 to 0.95; for further calculations, taking into account the gravity flow sheet, it was taken to be equal to 0.90) [20]:

$$Q_{Me} = V_{Me} \cdot E_{Me} \cdot k_{ben.}, \quad (2)$$

where Q_{Me} is the quantity of extractable metal, t, E_{Me} is the metal recovery into concentrate, %.

The annual flow of metals *P*, coming with newly disposed ash continuously generated by MCPP, which can also be involved in beneficiation, were separately calculated:

$$P_{Me} = Z_{ZShO-1} \cdot a_{Me} \cdot E_{ME} \cdot k_{ben.}, \quad (3)$$

where P_{Me} is the flow of extracted metal, t; Z_{ZSho-1} is the annual volume of "new" ash and slag disposed in dumps, t; a_{Me} is the initial metal grade, %; E_{Me} is the metal recovery into concentrate, %; $K_{ben.}$ is the coefficient taking into account total losses.

The values of the quantities of metals planned for recovery, calculated using the formulas above, are summarized in Table 4.

Table 2

Component composition percentages in MCPP ash

Sample	Si	AI	Fe	Sa	K	Ti	Mg	P	Sr	Mn	Zr	Cu	Zn	Rb	S
	%														
1	52.30	20.20	15.30	4.20	3.50	1.60	1.10	0.70	0.50	0.20	0.10	0.10	0.04	0.03	–
2	55.00	20.10	10.80	4.70	4.60	1.80	1.30	0.60	0.30	0.10	0.10	0.10	0.03	0.03	0.40
3	54.40	20.30	13.20	3.40	3.90	1.80	1.20	0.80	0.60	0.20	0.20	0.10	0.04	0.04	–
4	56.30	21.20	10.10	3.40	4.30	2.00	0.90	0.70	0.50	0.10	0.20	0.05	0.04	0.03	0.20
5	40.20	18.20	23.00	8.10	3.30	2.30	1.80	0.50	0.80	0.30	0.30	0.10	0.10	0.05	1.00
6	51.30	17.70	17.90	0.21	3.80	1.70	1.20	0.50	0.40	0.30	0.20	0.10	0.03	0.04	0.10
7	55.00	20.80	10.60	4.20	4.40	2.10	1.30	0.60	0.40	0.20	0.20	0.10	0.05	0.04	–
8	51.50	20.20	11.70	5.00	0.10	3.10	0.90	0.05	0.20	0.20	0.20	0.10	0.04	0.10	0.90

Table 3

Operational parameters for beneficiation of MCPP ash-and-slag waste

Metal	Initial percentage *a*	Marketable concentrate percentage *b*	Tailings percentage *o*	Concentrate yield $y_{conc.}$	Tailings yield $y_{tail.}$	Total recovery *E*, %
Ti + Zr	2.20	45.00	0.50	3.82	96.18	78.14
Sr	0.50	25.00	0.10	1.61	98.39	80.32
Fe	14.00	65.00	4.00	16.40	83.61	76.11

Table 4

Quantities of metals to be extracted

Metal	Quantity at Ash-and-Slag Dump-1 (ZShO-1) V_{Me}, tons	Extractable quantity Q_{Me}, tons	Annual incoming quantity P_{Me}, tons	Planned quantity to be extracted P_{Me} + 3% Q_{Me}, tons
Ti (me-1)	71,493.40	50,279.07	634.35	785.19
Sr (me-2)	16,248.50	11,745.90	148.19	183.43
Fe (me-3)	454,958.00	311,651.56	3,931.97	4,866.92

Taking into account the obtained values, the annual productivity by ash was calculated, and on this basis, the equipment and machinery were selected to provide the processing process:

$$U_{\text{ash}} = \frac{\sum_{Me\text{-}1}^{Me\text{-}3} P_{Me} + 3\% Q_{Me}}{AVG_{y_{c-t}}} \cdot AVG_{y_{t-n}}, \quad (4)$$

where U_{ash} is the annual productivity by ash, tpy, $AVG_{y_{c-t}}$ is the arithmetic mean of concentrate yield, % (7.32%), and $AVG_{y_{t-n}}$ is the arithmetic mean of tailings yield, % (92.72%).

The obtained value is 63 000 tons of ash processing per year, or 24 tons per hour. Selecting equipment and machinery based on these indicators is a straightforward task and does not require additional consideration.

The last task of calculating basic economic indicators was solved using analytical and computational methods for assessing the economic efficiency of innovation projects. Capital investments and operating costs were evaluated by analogy with similar technical projects for the mining and processing of alluvial rare metal material, with a discount rate of about 12%. Furthermore, based on the volumes of potential shipments of metal concentrates, the following indicators were calculated: NPV for a period of ten years and IRR for the same period. In the calculated rigid model, straight-line depreciation was used.

Input total expenditures amount to 188.50 mln rubles (CAPEX category – capital expenditures), and operating expenditures amount to 128.31 mln rubles per year (OPEX category – operating expenditures). The OPEX structure is as follows: 23.00% for the salary fund (the headcount is twenty-seven persons); 77.00% for material and operational maintenance costs, depreciation, and debenture interests.

The planned supply is based on the annual flow of a recoverable metal and the involvement of an additional 3% of accumulated recoverable metal in processing. In monetary terms, this amounts to 177.84 mln rubles. In this scenario, categorized as realistic, the accounting for the strontium metal yield is greatly underestimated due to the expected difficulties in extracting 183.43 tons of strontium per year. Only half of this quantity, i.e. 91.5 tons of strontium, was included in the model. The selling price of the shipped titanium concentrate was taken from open internet sources, at 66.00 thousand rubles per ton of concentrate (as of November 2022). The strontium concentrate's selling price is 96.00 thousand rubles per ton, and that of magnetite concentrate is 6.75 thousand rubles per ton[4].

The purchase of equipment and machinery is planned to be financed through borrowing from large financial organizations. Loan terms and conditions are 18.00% p.a. in rubles for a period of five years for fixed assets, and a second credit line for ensuring production activities at 12.0% p.a. in rubles for a period of three years. The structure of the borrowed capital is 54.0% for the main credit line, 42.0% for the second credit line, and 4.0% for attracted external financing.

The discount rate is 12% p.a. in rubles, given the current economic situation. Cash flows are presented in real terms. Only the final cash flow used to calculate NPV was adjusted for the inflation rate forecasted by the Ministry of Economic Development of the Russian Federation.

For the sake of illustrating the model, the assumption that the taxable base is formed exclusively in the period in which the settlement with budgets of various levels takes place was introduced. The model used the following tax rates: VAT at 20.0%, profit tax at 15.5%, and corporate property tax at 2.2%.

The model obtained based on the calculations results is shown in Table 5.

[4] Titanium concentrate. Starov & Co. URL: https://www.iodine.ru/ (accessed date: 20.11.22).

Table 5

Flexibility within a rigid model

Item	Indicator value, realistic model	Indicator value, pessimistic model	Indicator value, optimistic model
NPV, mln rubles	424.31	–31.40	657.65
IRR, %	42.00	9.00	66.00
ROS, %	29.00	7.00	39.00
PB, years	4.00	N/A	2.00
DPB	Does not exceed the forecasting time-frame	Exceeds the forecasting time-frame	Does not exceed the forecasting time-frame

The models were formed mainly depending on the changes in the selling prices of metals and the actual strontium sales indicator. In the pessimistic model, strontium is completely excluded from the calculation, and the selling prices for titanium and magnetite are underestimated by 10% compared to the current prices.

Practical application

Justifying economic efficiency is a mandatory stage in developing a rational flow sheet for ash and slag waste processing. One promising area for using the obtained results is the separation of the metal-bearing fraction and subsequent additional beneficiation to obtain concentrates of rare metals. These results will be presented to PJSC Magadanenergo as part of the investment proposal for the project of ash and slag waste processing at MCPP.

Another application of the performed economic efficiency substantiation is the planning by the university of the loading of its own laboratory for mineral beneficiation within the framework of a tolling agreement (an agreement on rendering services on processing of basic raw materials with transfer of finished bulk or selective concentrates to the customer) with PJSC Magadanenergo, should a decision be made on processing the ash and slag wastes to extract rare metals into a separate concentrate.

Findings Discussion

In the course of the study, the performance of the beneficiation process and the aggregated values of economic indicators for the implementation of this project on an industrial scale were calculated. Despite modest performance and low capital costs, the economic effect in two of the three scenarios (optimistic and realistic) appears attractive. However, the high risk of the results obtained due to some assumptions made in the study should be noted.

The first assumption relates to the limited accessibility of the region in relation to the central traffic arteries of the Russian Federation. This results in logistical complexity and a high final price for the consumer, making it difficult to find a buyer at the realizable cost mentioned above. The market saturation with ilmenite concentrate also decreases the attractiveness of the distant Magadan titanium dioxide and magnetite for potential buyers.

The second assumption concerns the effectiveness of strontium extraction technology gravity in the gravity beneficiation processes, which, due to the specific chemical compounds of strontium, also introduces certain risks.

Moreover, if the question of complete processing of the entire ash and slag dump of MCPP at the current site or a second site arises, there will be certain difficulties. These are directly related to the instability of coal deliveries to MCPP from the same producer, affecting both scheduled and off-schedule indicators governing the economics of the beneficiation process. The problem can be addressed by answering two questions, but this is only possible after the commencement of the MCPP ash beneficiation project and full-fledged exploration works:

1) Was the content of titanium dioxide in the ash of coal supplied to MCPP in previous years the same as currently?

2) Will the content of titanium dioxide in the ash of coal to be supplied to MCPP in the future be the same as currently?

The final assumption made concerns the confidence that the metals are distributed in such minerals and fraction from which they will be relatively easily extracted into an intermediate concentrate by gravity beneficiation and further upgraded in small volumes in the SVSU beneficiation laboratory. This question also requires further study.

Conclusion

The information obtained from various sources, along with the primary process design and semi-quantitative analysis of performance, appears to demonstrate the cost-effectiveness of the proposed process solutions. The beneficiation process flow sheet can be implemented not only as a stationary complex within a separate building but also as an open modular installation, which would allow for relocation to a second ash dump site in the future.

Meanwhile, the economic feasibility of the ash processing project in two of the three models showed good economic performance over a ten-year horizon. The project's implementation can also be effective in terms of improving the environmental situation, as it allows for the processing of up to 10% of the total volume of the ash dumps. This ensures fulfillment of one-fifth of the requirements of the Energy Strategy of the Russian Federation up to 2035[5].

The research is planned to continue with an additional study of the elemental and mineralogical composition of the ashes to determine the main minerals hosting the useful components planned for extraction.

---

[5] Energy Strategy of the Russian Federation for the period up to 2035. Ministry of Energy of the Russian Federation; 2020. URL: https://minenergo.gov.ru/node/1026 (accessed date: 20.11.22).

eISSN 2500-0632
https://mst.misis.ru/

References

1. Bazhenov Y.M., Shchebenkin P.F., Dvorkin L.I. *Application of industrial waste in the production of construction materials*. Moscow: Stroyizdat Publ.; 1986. 120 p. (In Russ.)
2. Borisenko L.F., Deltsin L.M., Vlasov A.S. *Prospects of utilization of ash from coal-fired thermal power plants*. Moscow: CJSC Geoinformmark Publ.; 2001. 68 p. (In Russ.)
3. Liu H., Banerji Sh.K., Burkett W.J., VanEngele J. Environment properties of fly ash bricks. In: *World of Coal Ash (WOCA) Conference*. Lexington, KY, USA, May 4–7, 2019.
4. Vereshchagina T.A., Kutikhina E.A., Buyko O.V., Anshits A.G. Hydrothermal synthesis and sorption performance to Cs(I) and Sr(II) of zirconia-analcime composites derived from coal fly ash cenospheres. *Chimica Techno Acta*. 2022;9(4):20229418. https://doi.org/10.15826/chimtech.2022.9.4.18
5. Lanzerstorfer C. Pre-processing of coal combustion fly ash by classification for enrichment of rare earth elements. *Energy Reports*. 2018;4:660–663. https://doi.org/10.1016/j.egyr.2018.10.010
6. Leonov S.B., Nikolskaya N.I.I., Vlasova V.V. CPP ashes – a possible raw material for obtaining iron concentrates. In: *Collection of Scientific Papers "Knowledge into Practice"*. Irkutsk: IrSTU Publ.; 1999. Pp. 6–9. (In Russ.)
7. Cherepanov A.A. Precious metals in the ash-cinder waste of Far Eastern heat-and-power stations. *Tikhookeanskaya Geologiya*. 2008;27(2):16–28. (In Russ.)
8. Cherepanov A.A., Kardash V.T. Complex processing of ash and slag wastes from CPPs (results of laboratory and semi-industrial tests). *Geology and Mineral Resources of World Ocean*. 2009;(2):98–115. (In Russ.)
9. Bakunin Y.N., Cherepanov A.A. Gold and platinum in ash and slag wastes of Khabarovsk CPP. In: *Ore Processing. Collection of Scientific Papers*. Irkutsk: IrSTU Publ.; 2003. Pp. 65–80. (In Russ.)
10. Karnaukhov Yu.P., Sharsva V.V., Podvolskaya E.N. Binders on the basis of waste ash-and-slag mixture and liquid glass from microsilica. *Stroitel'nye Materialy*. 1998;(5):12–13. (In Russ.)
11. Kizilstein L. Ya., Shpitsgluz A. L., Rylov V. G. Aluminosilicate microspheres of pulverized coal combustion ash. *Khimiya Tverdogo Topliva*. 1987;(6):122–124. (In Russ.)
12. Gayday N.K., Kuzmenkov M.A., Shipunov L.V. Analysis of coals and ashes of the Magadan CHPP. *Aktual'nyye Nauchnyye Issledovaniya v Sovremennom Mire*. 2021;12–11(80):253–261. (In Russ.)
13. Shipunov L.V., Kuz'menkov M.A., Gaiday N.K. Characteristics of ash and ash dumps of Magadan TPP. In: *Ideas, hypotheses, search... Materials of the XXVII Regional Scientific Conference of Postgraduate Students, Degree-Seeking Students, and Young Researchers*. Magadan, April 21, 2022. Moscow: Znanie-M Publ.; 2022. Pp. 223–232. (In Russ.) https://doi.org/10.38006/00187-196-5.2022.223.232
14. Shipunov L.V., Kuzmenkov M.A., Gaiday N.K. Estimation of rare metal content distribution in an ash dump of Magadan CPP. In: *At the Crossroads of the North and the East (Methodologies and Practices of Regional Development): Proceedings of the IV International Scientific and Practical Conference*. Magadan, November 17–18, 2022. Magadan: SVSU Publ.; 2022. Pp. 214–220 (In Russ.)
15. Polkin S.I. *Ores and placers of rare and precious metals beneficiation.* 2nd ed., reprint and additional. Moscow: Nedra Publ.; 1987. Pp. 123–169. (In Russ.)
16. Egorov V. N. *Mineral Processing*. Moscow: Nedra Publ.; 1987. Pp. 28–56. (In Russ.)
17. Shipunov L.V., Kuzmenkov M.A., Gaidai N.K. Mapping of ash and slag dumps of Magadanskaya TPP. In: *Innovative trajectory of modern science development: collection of papers*. Petrozavodsk: "New Science" International Center for Science Partnerships; 2022. Pp. 125–131. (In Russ.)
18. Adeeva L.N., Borbat V.F. Ashes of heating and power plant – perspective raw material for industry. *Herald of Omsk University*. 2009;(2):141–151. (In Russ.)
19. Atkinson A.A., Banker R.D., Kaplan R.S., Yuong S.M. *Management accounting*. 3rd ed. New Jersey: Pearson College Div; 2000. (Trans. ver.: Atkinson A.A., Banker R.D., Kaplan R.S., Yuong S.M. *Management accounting*. 3rd ed.: trans. from English. Moscow: Williams; 2005. Pp. 321–457. (In Russ.))
20. *Ore processing plant design handbook*. In 2 Books, Book 1. Compiled by: Baranov V.F. et al.; editors: Prof. Tikhonov O.N. et al. Moscow: Nedra Publ.; 1988. Pp. 194–209. (In Russ.)

Information about the authors

Lev V. Shipunov – Senior Lecturer at the Department of Digital Engineering, North-Eastern State University, Magadan, Russian Federation; ORCID 0000-0002-0840-8209; e-mail Eazey2308@gmail.com

Maxim A. Kuzmenkov – Senior Lecturer at the Department of Digital Engineering, North-Eastern State University, Magadan, Russian Federation; ORCID 0000-0002-6375-9693, Scopus ID 58286501200; e-mail Snowfallandtea@mail.ru

Nataliya K. Gaidai – Cand. Sci. (Eng.), Associate Professor, Director of the Polytechnic Institute, North-Eastern State University, Magadan, Russian Federation; Senior Researcher at the Laboratory of regional Geology and Geophysics, North-Eastern Integrated Research Institute named after N.A. Shilo of Far Eastern Branch of the Russian Academy of Sciences, Magadan, Russian Federation; ORCID 0000-0002-2679-4967, Scopus ID 6603868070; e-mail nataly_mag@rambler.ru

Received 07.05.2023
Revised 06.10.2023
Accepted 01.11.2023