forfeited foreign markets by the domestic market, regarding the fact that the pattern of the demand ecologization becomes increasingly more noticeable;

Fourth, three ascertained challenges facing the Russian fuel and energy sector (the green transition, retargeting of sales markets, demand ecologization) offer both adverse after-effects and new growth sources which can facilitate better sustainability of the fuel and energy sector in Russia. In the gas industry, this means integration of natural gas and natural hydrogen recovery and manufacture of energy products at high added value. In the oil industry, this means a gradual rejection of oil recovery and replacement of oil by renewable sources, for instance, biomass.

References

1. Mišík M., Nosko A. Post-pandemic lessons for EU energy and climate policy after the Russian invasion of Ukraine: Introduction to a special issue on EU green recovery in the post-Covid-19 period. *Energy Policy*. 2023. Vol. 177. ID 113546.
2. Beatley T. Green urbanism: Learning from European cities. Washington, DC: Island press, 2012. 512 p.
3. Aganbegyan A. Will the fuel and energy complex remain the driver of the Russian economy? *Energy Policy*. 2022. No. 2(168). pp. 44–53.
4. Hurst H. E. Long-term storage capacity of reservoirs. *Transactions of the American society of civil engineers*. 1951. Vol. 116, Iss. 1. pp. 770–799.
5. World's Energy Statistics. Enerdata. 2023. Available at: https://energystats.enerdata.net/ (accessed: 20.06.2024).
6. Hunt J. D., Nascimento A., Nascimento N., Vieira L. W., Romero O. J. Possible pathways for oil and gas companies in a sustainable future: From the perspective of a hydrogen economy. *Renewable and Sustainable Energy Reviews*. 2022. Vol. 160. ID 112291.
7. Vuppaladadiyam A. K., Vuppaladadiyam S. S. V., Sahoo A. et al. Bio-oil and biochar from the pyrolytic conversion of biomass: A current and future perspective on the trade-off between economic, environmental, and technical indicators. *Science of the Total Environment*. 2023. Vol. 857. ID 159155.
8. Antonakakis N., Cunado J., Filis G., Gabauer D., De Gracia F. P. Oil volatility, oil and gas firms and portfolio diversification. *Energy Economics*. 2018. Vol. 70. pp. 499–515.
9. Chen G. Q., Chen Z. M. Greenhouse gas emissions and natural resources use by the world economy: ecological input–output modeling. *Ecological Modelling*. 2011. Vol. 222. Iss. 14. pp. 2362–2376.
10. Official Statistics. Rosstat. 2023. Available at: https://rosstat.gov.ru/folder/10705 (accessed: 20.06.2024).
11. Kaukin A. S., Miller E. M. Reducing the damper will reduce super profits of Russian refineries, but will not make them unprofitable. *Russian Economic Developments*. 2023. Vol. 30, No. 7. pp. 29–33.
12. Korchagina S. A. Sustainability issues in the oil and gas sector: Relevance, perspectives. *The Eurasian Scientific Journal*. 2022. Vol. 14. No. 3. EM

UDC 330.341.1:669:662

B. R. RAKISHEV [1], *Academician of NAS RK, Professor, Doctor of Engineering Sciences, b.rakishev@satbayev.university*

[1]*Satbayev Kazakh National Research Technical University, Almaty, Kazakhstan*

MINERAL–INDUSTRIAL MEGA COMPLEX — THE BASIS OF SCIENTIFIC AND TECHNOLOGICAL PROGRESS

The mineral–industrial mega complex (MIMC) in Kazakhstan is described. The place of the complex in the world mineral resources and reserves is shown, and the volumes of the main products of MIMC during the last years are given. The high-priority objectives of MIMC in modern conditions are highlighted. The mathematical models of mineral raw materials at each stage of mining and processing are given. On this basis, recommendations on integrated and comprehensive utilization of mineral resources are given. The technical and economic criteria are substantiated for selecting effective methods for extraction of rare earth metals (REM) from multi-component ores. It is shown that new technologies and equipment adaptable to natural and process properties of a raw material from a particular mineral object can provide high level of REM extraction in order to worthily represent MIMC in the world market of rare earth metals.

Keywords: *mineral–industrial mega complex, scientific and technological progress, civilization stages, process raw materials, rare earth metals, mathematical models of mineral raw materials, innovative technologies*

DOI: *10.17580/em.2024.02.11*

Introduction

Industrialized mining countries establish mining-related sectors connected with minerals, oil and gas, metallurgy, chemistry, fuel and energy, nonmetals and construction. These sectors deal with geological exploration, extraction and processing of raw materials for production of feedstock for manufacturing industries. Operations in all these sectors start with extraction of mineral reserves from the subsoil. Technologies and equipment used in mining and processing of minerals are the same in principle but have different designs to be adaptable to various industries.

Similar in essence but different in purpose, mineral mining and processing works should be integrated to single mineral industry mega complex (MIMC). Such approach can help objectively estimate the role of MIMC in advancement of science and technology, and effectively control production of process feedstock for the high-tech manufacturing industries.

History of civilization exhibits its direct connection with the use of mineral resources of the Earth. Depending on the level of processing of mineral raw materials to be used as implements, ancient sophists identified the Stone, Bronze and Iron Ages [1–5].

Starting from the mid-18th century, civilization developed under the influence of the science and technology progress based on the mass use of widely ranged high-quality metals and alloys for creating production tools—various-purpose machines.

Having taken its rise in the middle of the 20th century, the scientific and technological revolution worked greatly on the pace of industrial development. It became possible to transit to high technologies and equipment based on the use of earlier unknown diverse alloys of ferrous, nonferrous, noble and rare earth metals extracted from minerals [6–17].

As seen, at all civilization stages, the product of the mineral–industrial mega complex is a physical and technological basis of the scientific and technological progress. The science and technology progress, in its turn, is what

© Rakishev B. R., 2024

initiated and is initiating innovations in all sectors of economy, including the mineral–industrial mega complex [9–19].

Mineral–industrial mega complex

A mineral–industrial mega complex (MIMC) should be understood as an aggregate of existing (projected) sectorial industrial complexes dealing with geological exploration, mining and processing of natural or manmade mineral raw materials for the production of a feedstock for manufacturing industries. MIMC comprises the geological exploration, hydrogeology, oil and gas, mining-and-metallurgy, mining-and-chemistry, fuel, nonmetal and mining-and-construction complexes. The structure of MIMC is described in **Fig. 1**.

The object of study and production activity in all above-listed complexes are mineral deposits, and the product of each complex is a feedstock for the next process stage. These components of the mineral–industrial mega complex are shown in **Fig. 2**.

The product of the mineral–industrial mega complex is a feedstock for the construction, metallurgy, machine engineering, chemistry and other high-tech industries.

Geological exploration complex is a family of different specialized geological agencies engaged in geological exploration aimed at studying occurrence, formation, structure and material composition of minerals and rocks at specific deposits.

Geological exploration is carried out at promising objects of certain raw materials after proper appraisal and appreciation. Geological exploration is aimed at provision of reliable data for tenable geological, technological and economical evaluation of a commercial value of a mineral deposit. Regarding oil and gas reservoirs, their structure is studied, productive strata are identified, and potential oil/gas/condensate/water flow rates, reservoir pressure and other characteristics are determined.

The end product of this complex are the proven mineral reserves of a certain quality and at a certain deposit. This is a framework for the design and operation of mines and processing factories.

Hydrogeology complex is a group of special agencies and services which study origination, occurrence, composition and flow patterns of groundwater, as well as interaction of groundwater with rocks, surface water and atmosphere. The studies are the source data for the design and operation of water supply, irrigation and melioration structures, for the analysis of environmental impacts of hydraulic engineering (water reservoirs, etc.), as well as consequences of utilization of underground, drink, process, mineral, thermal and waste water, and deep disposal of industry waste, and for the prediction of water ingresses in traffic tunnels and in surface or underground mines.

The end product of this complex is the hydrogeological information about a certain object for the construction and operation of groundwater utilization structures, as well as for the determination of feasibility of domestic and industrial water supply.

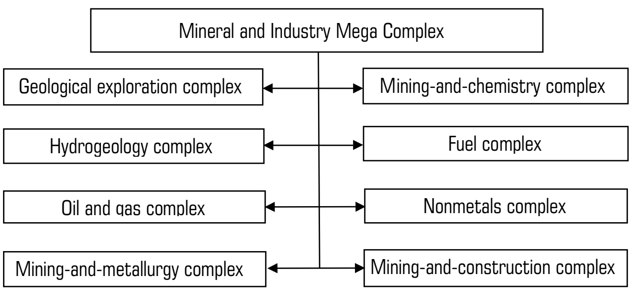

Fig. 1. Structure of mineral–industrial mega complex

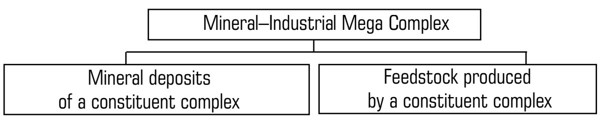

Fig. 2. Components of mineral–industrial mega complex

Oil and gas complex is a system of plants concerned with production, transport and processing of oil (oil industry) and gas (gas industry), and with distribution of oil and gas conversion products.

Oil and gas products are various fuels, benzene, kerosene, liquefied petroleum gas, diesel, oils, fuel oils, bitumen, paraffin, various solvents, lubricants, soot and natural gas.

The products of the oil and gas complex are the feedstock for the chemical, power, aircraft, light, automobile and railway industries.

Mining-and-metallurgy complex is a cluster of ore mines which supply raw materials for ferrous and nonferrous metallurgy to produce cast iron, steel, roll stock, tubes, hard components, wire rods, ferro-alloys, coke-chemical products, refractory materials, hard alloys, graphite products, nonferrous/noble/rare earth metals and their derivatives (alloys, foil, wire rod, wire, etc.).

The product of the mining-and-metallurgy complex is the feedstock for the civil and industrial engineering, machine engineering and instrument making, rocket and missile engineering, atomic and hydrogen energetics and all hi-tech industries.

Mining-and-chemistry complex is a totality of plants engaged in mining and processing of raw materials for the chemical industry — apatite, phosphate ore, common and potassium salts, sulfur-, boron-, arsenic- and barium-bearing ore, natural sodium sulfate, sodium bicarbonate, barium sulfate, iodine, bromine, etc.

The main products of the mining-and-chemistry complex are potash fertilizer, phosphate fertilizer, sodium chloride, natural sodium sulfate, borate, brassil and natural sulfur. Sulfur is mainly produced in processing of oil and natural gas (95%).

The product of the mining-and-chemistry complex is a feedstock for the chemical, agricultural, light, power generating and metallurgical industries.

Fuels complex is a part of the fuel and energy sector, which deals with mining and preparation of bituminous coal, lignite, bituminous shale, peat, oil, gas and uranium for the heat and nuclear power engineering, and for the chemical industry.

The product of the fuels complex is a feedstock for the chemical, metallurgical, power and agricultural industries.

Nonmetals complex is a system of plants engaged in mining and processing of natural and manmade mineral reserves for the production of construction and fabricating materials: granite, dolomite, kaoline, marl, chalk, feldspar, etc., as well as for the production of precious and ornamental stones.

The product of the nonmetals complex is a feedstock for the construction, automobile, road, railway, aircraft, metallurgy, power generating and light industries.

Mining-and-construction complex is a family of specialized construction organizations which select methods and means, and parameters of building and construction works in operating and mined-out underground roadways and tunnels to maintain long-term functioning of an underground (or above-ground) object.

The products of the mining-and-construction complex are the underground (above-ground) structures of various purpose (warehouses, storages, hydraulic power construction works, hospitals, subjects of science, culture, tourism, sports, etc.).

The product of the mining-and-construction complex is the manmade assets for the industry, agriculture, health care, culture and sport.

Overall view of MIMC is given in **Fig. 3**.

High-priority objectives of mineral–industrial mega complex of Kazakhstan

The modern mineral mining and ferrous/nonferrous metallurgy in Kazakhstan and in CIS countries typically faces worsening of geological conditions at actual and planned mineral deposits, reduction of content of useful

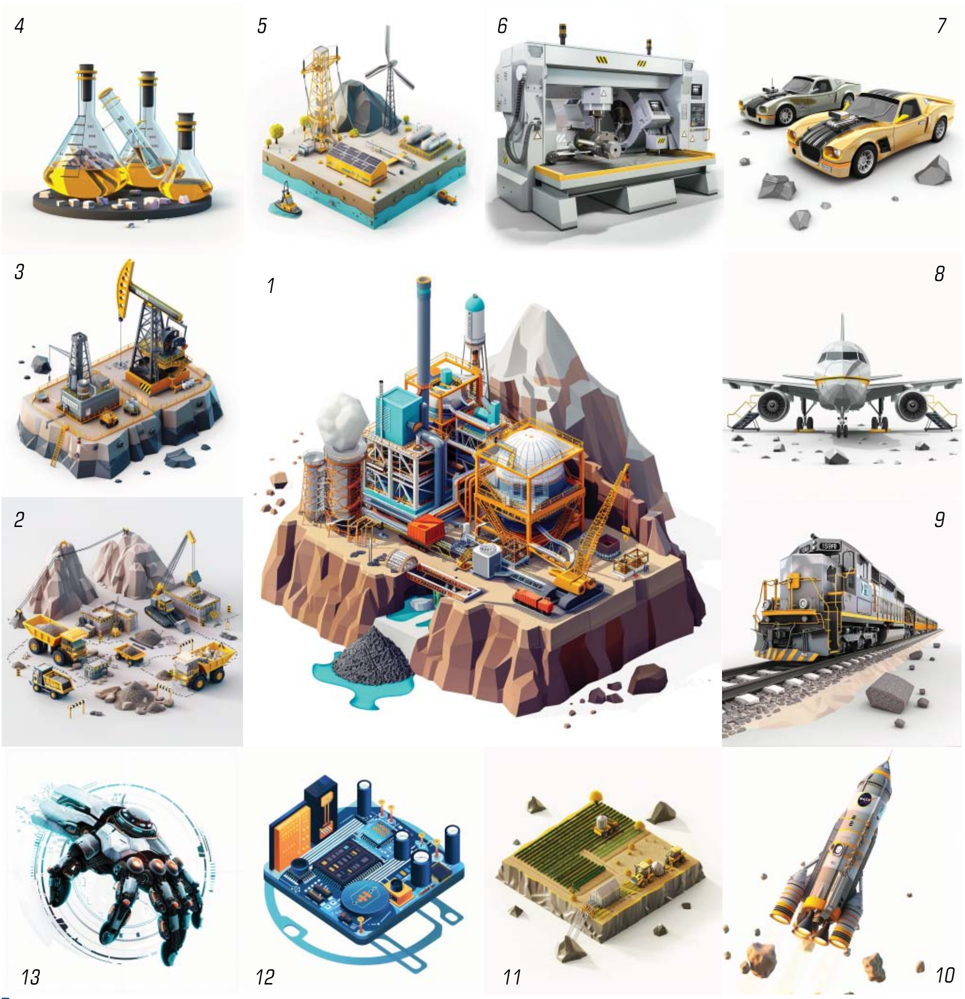

Fig. 3. Mineral–industrial mega complex (*1*) and its consumers (*2–13*)

components in ore, complication of ore mineral composition, increased percentage of refractory ore, etc. [20, 21].

In such circumstances, only full-capacity and integrated utilization of mineral raw materials can ensure competitiveness of business activities in this field. A high-priority objective is to speed up development and introduction of new technologies, processes and equipment aimed at complete extraction of all useful components contained in mineral raw materials to an end product, especially rare earth metals (REM).

Kazakhstan lacks specific REM deposits, while they are a prime source of metals and alloys necessary for the high technologies. REM are mainly contained in ferrous/nonferrous/noble metal ores, uranium, coal, oil, etc. For instance, nonferrous metal ores contain more than 20 critical noble and rare earth metals (gold, silver, platinum, palladium, ruthenium, selenium, tellurium, cadmium, rhenium, indium, osmium, thallium, etc.). The same list of associate REM is typical of oil, uranium and coal deposits [22–24].

Advanced and efficient technologies of mineral mining and processing can be chosen from mathematical modeling of a mineral raw material at each process stage. The mathematical models are given by:

$$M_{rr}=\sum_{i=1}^{n} m_i;\ M_{ex}=\varepsilon_{ex}\sum_{i=1}^{n} m_i;\ M_{lr}=\varepsilon_{ex}\sum_{i=1}^{r}\varepsilon_{ri} m_i;\ M_c=\varepsilon_{ex}\sum_{i=1}^{p}\varepsilon_{ci} m_i;$$
$$M_t=\varepsilon_{ex}\sum_{i=1}^{s}\varepsilon_{ti} m_i;\ \ \varepsilon_{ex}\sum_{i=1}^{q}\varepsilon_{ci}\varepsilon_{mi} m_i;\ \ M_{mw}=\varepsilon_{ex}\sum_{i=1}^{l}\varepsilon_{wi} m_i;$$
$$M_{ex}=M_{pp}+M_{lr},\quad M_c=M_m+M_{mw}, \tag{1}$$

where M_{rr} is the mass of registered reserves; M_{ex} is the mass of extracted ore; M_{pp} is the mass of ore shipped to processing plant; M_{lr} is the mass of lumpy rock removed from the ore mass; M_c is the mass of concentrate(-s); M_t is the mass of tailings; M_{mi} is the mass of an *i*-th end product (metal); M_m is the mass of the whole end product (all metals); M_{mw} is the mass of metallurgy waste; m_i is the mass of an *i*-th component in the registered reserves; *n* is the number of all components in the volume of minerals and barren rocks; ε_{ex} is the mineral extraction ratio; ε_{ri} is the coefficient of removal of an *i*-th lumpy ore from the ore mass; ε_{ci} is the extraction ratio of an *i*-th component from ore to concentrate; ε_{ti} is the extraction ratio of an *i*-th component from ore to tailings; ε_{mi} is the extraction ratio of an *i*-th metal to concentrate; ε_{wi} is the extraction ratio of an *i*-th component to metallurgical waste; *p* is the number of useful components extracted from ore to concentrate; *r* is the number of components removed from the ore mass; *s* is the number of components extracted to tailings; *q* is the number of useful components extracted from concentrate to metal; *l* is the number of components extracted from concentrate to metallurgical waste.

According to the existing mineral processing technologies, the condition that $n \geq p \geq q$ is always adhered to. In the generally accepted ore mining and processing technologies: $\varepsilon_{ex} = 0.5–0.97$ (the lower limit is for underground mining, the upper limit is for open pit mining), $\varepsilon_{ri} = 0.15–0.4$, $\varepsilon_{ci} = 0.4–0.98$, $\varepsilon_{ti} = 0.02–0.5$, $\varepsilon_{mi} = 0.85–0.98$, $\varepsilon_{wi} = 0.02–0.15$.

The analysis of the mathematical models (1) of a mineral raw material at each stage of its mining and processing shows that all technologies of geological exploration, mining, processing and chemicometallurgical circuits, aimed at improved quality and completeness of extraction of the main and associate useful components, consist in increasing the value of *n*, pushing the values of *p* and *q* toward *n*, raising the values of ε_{ex}, ε_{ri}, ε_{ci}, ε_{mi} and decreasing the values of ε_{ti} and ε_{wi}. This inference is reflective of the essence of technological and organizational decision-making aimed at enhanced completeness of mineral utilization.

Completeness of utilization of a mineral is evaluated using the formulas of the worth of the mineral in rock mass, in extracted ore, in concentrate and in metal:

$$W_{rm}=\sum_{i=1}^{n} m_i c_i,$$

$$W_{ore}=\varepsilon_{ex}\sum_{i=1}^{n} m_i c_i,\ W_c=\varepsilon_{ex}\sum_{i=1}^{p}\varepsilon_{ci} m_i c_i,\ W_m=\varepsilon_{ex}\sum_{i=1}^{q}\varepsilon_{ci}\varepsilon_{mi} m_i c_i, \tag{2}$$

where c_i is the cost of 1 t of an *i*-th end product.

The criterion (2) is important in substantiation of recovery of expensive rare earth metals (osmium, rhenium, tantalum, etc.) from mineral raw materials while the content of REM reach only a few hundred thousandth per cent. In such cases, the worth of REM by-recovery is comparable and even higher than the worth of the main useful components.

It is shown in [20] that technological innovations and high-technology equipment can raise the level of extraction by 2–2.5 times for noble and rare earth metals and by 1.5 times for basic metals. The aggregate profit of sales of associate noble and rare earth metals exceed the profit of sales of basic metals (copper, molybdenum) by 9.35 times. Given the integrated and complete utilization of ore, the present-day return on sales of the mining and metallurgy sector products in Kazakhstan can be ensured at the ore production volume at least 8–10 times less than the current mining output.

Thus, multi-component ore deposits in Kazakhstan, together with uranium, oil and manmade raw materials, are the stable source for the commercial production of noble metals and rare earth metals. New technologies and equipment adaptable to natural and process properties of a mineral raw material from a specific deposit can ensure high level of extraction of these metals.

For the large-scale introduction of integrated and comprehensive mineral utilization activities, it is required that government legislation develops and introduces economic instruments to stimulate maximization of extraction of associate useful and valuable components from mineral raw materials as the demand for such components grows in view of the needs of high technologies.

Conclusions

It is shown that the existing sectorial complexes concerned with mineral mining and processing are expedient to integrate in a single mineral–industrial mega complex.

The leading role of the mineral–industrial mega complex in the progress of human society, science and technology is validated.

The notion of the mineral–industrial mega complex is defined, and the characteristics of the mineral–industrial mega complex as a set of geological exploration, hydrology, oil and gas, mining-and-metallurgy, mining-and-chemistry, fuel, nonmetals and mining-and-construction complexes are given.

The present-day high-priority objectives of the mineral–industrial mega complex are displayed.

The mathematical models of mineral resources at each stage of mining and processing are presented. They are used as a framework for recommending integrated and comprehensive utilization of mineral raw materials.

The technical and economic criteria are substantiated for selecting efficient methods of REM recovery from multi-component ore.

It is shown that new technologies and equipment adaptable to natural and process properties of a mineral raw material from a specific mineral deposit can ensure high-level recovery of REM to worthily present MIMC on the global REM market.

Acknowledgements

The article is prepared within a project supported by the Ministry of Science and Higher Education of the Republic of Kazakhstan. Project 2023/AP19676591: Development of Innovative Technologies for Complete Extraction of Isolated Standard-Quality Ores from Structurally Complex Bench Blocks.

References

1. Prokhorov A. M. (Ed.). The Great Soviet Encyclopedia. 3rd ed. Vol. 9 : Euclid — Ibsen. Moscow : Sovetskaya entsiklopediya, 1972. 622 p.
2. Prokhorov A. M. (Ed.). The Great Soviet Encyclopedia. 3rd ed. Vol. 11 : Italy — Kvarkush. Moscow : Sovetskaya entsiklopediya, 1973. 608 p.
3. Prokhorov A. M. (Ed.). The Great Soviet Encyclopedia. 3rd ed. Vol. 4 : Brasos–Vesh. Moscow : Sovetskaya entsiklopediya, 1971. 500 p.
4. Palamarchuk O. T. Science and technological revolutions. *Ekonomika. Pravo. Pechat*. 2013. No. 4(60). pp. 81–88.
5. Rao J. S. History of Rotating Machinery Dynamics. Dordrecht : Springer Science, 2011. Vol. 20. 358 p.
6. Internet of Things (IoT) in Russia: Already available technology of the future. PwC, 2017. Available at: https://www.pwc.ru/ru/publications/iot/iot-in-russia-research-rus.pdf (accessed: 23.06.2019).
7. Skhvediani A. E., Gorovoy A. A. The fourth industrial revolution as the ground for the transition to the sixth technological mode. *Urgent Questions of Economy and Management : II International Scientific–Technical Conference Proceedings*. Novosibirsk : Izdatelstvo TsRNS, 2017. pp. 55–59.
8. Clark G. The New Palgrave Dictionary of Economics. 3rd ed. London : Palgrave Macmillan, 2018. 14896 p.
9. Rakishev B. R. Mining, metallurgy and development of civilization. *Gornyi Zhurnal*. 2019. No. 9. pp. 33–37.
10. Kablov E. N., Ospennikova O. G., Vershkov A. V. Rare metals and rare-earth elements — Materials for modern and future high technologies. *Trudy VIAM*. 2013. No. 2. Available at: http://viam-works.ru/ru/articles?art.id=9 (accessed: 20.06.2024).
11. Leleu S., Rives B., Bour J., Causse N., Pébère N. On the stability of the oxides film formed on a magnesium alloy containing rare-earth elements. *Electrochimica Acta*. 2018. Vol. 290. pp. 586–594.
12. Tebekin A. V., Anisimov E. G., Tebekin P. A., Egorova A. A. Analysis of signs of the forth industrial revolution in the Industry 4.0 Initiative. *Transport business in Russia*. 2021. No. 2. pp. 13–21.
13. Akayev A. V. Transition of industrial society to postindustrial: impact of scientific and technical progress. *Herald of GSOTU. Humanitarian, Social and Economical Sciences*. 2020. Vol. 16, No. 2(20). pp. 35–39.
14. Vertakova Yu. V., Polozhentseva Yu. S., Maslennikova V. V. Industrial transformation in the context of the digitalization of the economy: Implementation features and trends. *Economics and Management*. 2021. Vol. 27, No. 7. pp. 491–503.
15. Ilyanovich E. B. Science and technics on the threshold of the fourth technological revolution in modern technogenic civilization. *Vestnik of Northern (Arctic) Federal University. Series: Humanitarian and Social Sciences*. 2021. Vol. 21, No. 4. pp. 100–110.
16. Hottois G. Techno-Sciences and Ethics. Evandro Agazzi: Right, Wrong and Science. Leiden: Brill. 2004. Vol. 81. pp. 261–265.
17. Khramchenko A. A., Chernaya O. A., Goroditsky A. A., Bulgar O. Yu. Efficiency of scientific and technological progress (STP). *Natural–Humanitarian Studies*. 2021. No. 36(4). pp. 261–267.
18. Amol S. Patil, Arun V. Patil, Chandrakant G. Dighavkar, Vishnu A. Adole, Umesh J. Tupe, Synthesis techniques and applications of rare earth metal oxides semiconductors: A review. *Chemical Physics Letters*. 2022. Vol. 796. ID 139555.
19. Sims Z. C., Kesler M. S., Henderson H. B. et al. How cerium and lanthanum as coproducts promote stable rare earth production and new alloys. *Journal of Sustainable Metallurgy*. 2022. Vol. 8. pp. 1225–1234.
20. Rakishev B. R. Mining industry is the foundation of scientific and technical progress. *25th World Mining Congress*. Astana. 2018. pp. 161–169.
21. Rakishev B. R. New definitions of natural and transformed mineral deposits, and their exploitation stages. *MIAB*. 2023. No. 8. pp. 165–177.
22. Gaustad G., Williams E., Leader A. Rare earth metals from secondary sources: Review of potential supply from waste and byproducts. *Resources, Conservation and Recycling*. 2021. Vol. 167. ID 105213.
23. Lukowiak A., Zur L., Tomala R. et al. Rare earth elements and urban mines: Critical strategies for sustainable development. *Ceramics International*. 2020. Vol. 46, Iss. 16. P. B. pp. 26247–26250.
24. Costis S., Mueller K. K., Coudert L. et al. Recovery potential of rare earth elements from mining and industrial residues: A review and cases studies. *Journal of Geochemical Exploration*. 2021. Vol. 221. ID 106699. EM