

New Technologies of Comprehensive Recovery of Valuable Components from Minerals: Current Status and Further Progress

V. A. Chanturiya

*Research Institute of Comprehensive Exploitation of Mineral Resources, Russian Academy of Sciences,
Kryukovskii tupik 4, Moscow, 111020 Russia*

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Abstract—The main lines of basic research in the field of comprehensive processing of minerals are considered, and the current status of development of new technologies in Russia and abroad is compared. Alternative processes of intergranular disintegration of mineral complexes, as well as highly efficient and environmentally safe technologies of refractory ore processing, are discussed.

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INTRODUCTION

Rigid requirements on the quality of concentrates, on the one hand, and involvement of refractory ores and coal of complex composition in processing, on the other hand, are characteristic attributes of the current status of the mining, metallurgical, fuel, and energy industries in Russia. Low grades of valuable components; fine, up to emulsive, disseminations of mineral complexes; and similar technological properties of minerals typically stand in the way of recovery of valuable components.

Over the last two decades, the grade of base metals in ore has decreased by 1.3–1.5 times and that of iron and gold, by 1.25 times; the percentage of refractory ore and coal has increased from 15 to 40%.

After the breakup of the Soviet Union, Russia lost economic deposits of manganese, chrome, kaolin, and some other mineral resources. With the entry of Russia into the world market, the requirements on the quality of concentrates increased sharply with regard to both technological and environmental protection standards.

Preliminary calculations show that the majority of ore deposits of Russia previously included in the State Register of Reserves may be placed in the category of subeconomic ore because, taking into account world prices for the final products, their mining using traditional technologies is unprofitable. The reappraisal of deposits with consideration of this factor has shown that 34% of lead deposits; 49% of tin deposits; 34% of magnetite deposits; and 15–30% of titanium, copper, tungsten, apatite, and coal deposits should be regarded as subeconomic.

Thus, the current status of mineral resources, i.e., the necessity of involvement of refractory ore in pro-

cessing and the difficult environmental situation in mining districts, comes into conflict with the status of technical and technological capabilities and organization of the primary processing of minerals at mining and concentrating plants.

Under these conditions, enhancing the completeness and comprehensiveness of mineral concentration by using highly efficient and environmentally safe technologies becomes a top priority. It should be based on intensifying existing and creating new modes of recovery of valuable components from refractory ores and technogenic deposits.

GENERAL DESCRIPTION OF THE FIELD

Concentration of mineral resources is a branch of mining science and geology (mineralogy) and comprises the knowledge on recovery of valuable components from minerals, including technological mineralogy; disintegration of minerals and their preparation for concentration; and physical and chemical separation, concentration, and processing of minerals. These lines of research are focused on developing the theoretical bases of separation processes and designing concentrating apparatuses, as well as on providing insights into the distribution of ore components and the conditions of separation of products of concentration with the aim of enhancing the selectivity and rate of separation and its efficiency, economy, and environmental safety.

The efficiency of concentration of mineral resources predetermines in many respects the economics of the mining and metallurgical industry. The greatest losses of valuable components on the path from the mine to the metallurgical works are the stage of concentration, where losses reach 10–30%. Therefore, obtaining new knowledge on the physical and physicochemical prop-

erties of minerals and new methods for increasing the contrast of properties of separated components and for disintegration and opening of refractory ore is a leading line of scientific research. Solving these problems will enable design and development of new methods and new equipment ensuring the involvement of complex ores in processing and the high and comprehensive recovery of all valuable components. Rapid progress in this direction is possible only with the use of current achievements in solid-state physics, high-energy physics, physical and organic chemistry, and electrochemistry.

Priority Lines of Research

(1) Development of physical and physicochemical methods and software–hardware complexes for rapid mineralogical and technological assessment of natural and technogenic mineral deposits.

(2) Scientific substantiation and development of alternative processes of intergranular disintegration of mineral complexes, enhancement of contrast in mineral properties, and opening of refractory ore.

(3) Development of new, environmentally safe processes aimed at comprehensive refractory ore processing based on the combination of efficient concentration methods with pyro- and hydrometallurgical processes.

(4) Elaboration of a theory and technology of processing of technogenic minerals and new methods of conditioning of hydrous and gas phases.

In the near future, new data on mineral and ore formation will make it possible to develop a new line of scientific research related to the production of minerals with prescribed properties (doped with certain components) at the final stage of primary ore processing.

Over recent decades, considerable advances have been made by Russian science in the area of basic research and development of new processes of recovery of valuable components from minerals. As may be judged from the proceedings of the International Mineral Processing Congress, the level of new knowledge and scientific and technical developments of Russian specialists is on par with the world level. At the same time, compared with developed foreign countries, Russia remains behind in development of the machine-building basis of the production of concentrating equipment, its quality, the specific amount of metal and energy per structure, and its durability.

In recent years, increasing efficiency of recovery of valuable components from ore has been achieved at the expense of combined processes, new reagent-free methods of increasing the contrast in properties of separated minerals, bioprocesses, energy methods of management of mechanical and physicochemical properties of minerals, and heap and underground leaching.

IMPORTANT SCIENTIFIC PROBLEMS

Development of a Software–Hardware Complex for Rapid Mineralogical and Technological Assessment of Natural and Technogenic Mineral Deposits on the Basis of Image Analysis

Because of involvement of refractory ores of complex composition in processing, worsening of the environmental situation, and the necessity of processing technogenic materials, the rapid forecasting of the technological properties and dressability of natural and technogenic minerals has become especially important. The reliability of such estimates depends, to a considerable degree, on the completeness of study of the mineral composition and the accuracy of determination of technologically significant factors. The mineral composition, the dimensions of minerals, and their phase composition are investigated with modern physical, physicochemical, and chemical methods. The study of the structural parameters of ores, mineral aggregates, and opening of phases through all cycles of processing allows us to obtain reliable and complete information on the technological properties of ores, optimize ore preparation and separation of mineral components, and forecast mineral concentration.

Technological estimation with image analysis not only provides the possibility of a scientifically based forecast of the dressability of minerals and the technical and economic parameters of their processing, but also allows the implementation of examination of ready design solutions and certification of products and technological projects.

The unbiased quantitative estimation of the structural and phase characteristics of minerals at the stage of preliminary dressability forecasting may be performed only on the basis of sufficient statistical data (hundreds or thousands of mineral grains). At the same time, it must be done in brief periods of time. Quantitative automated image analysis with geometrical optical methods meets these requirements. Image analyzers, i.e., systems capable of rapid input and processing of complex images, are the most promising equipment for such purposes.

The development of the necessary element base has made it possible to create in Russia software–hardware complexes for image analysis that are comparable with the best foreign analyzers or even surpass them.

The first publications on use of image analysis for the study of mineral opening and morphometric, structural, and textural characteristics appeared in the early 1980s. The Magiscan (Great Britain) and IBAS (Germany) systems were used as image analyzers. These are multiprocessor systems with sequential or/and parallel structures. The systems are equipped with translators from higher level languages and have developed system libraries and a package of applied programs. However, the input system of these analyzers does not allow one to obtain measurements of satisfactory accuracy (the

resolution of the scene dimension is 0.5%, whereas, in Russian analyzers, it is 0.2%).

The most interesting scientific results of image analysis applied to estimation of sulfide disseminations in base-metal ore and mineral complexes in products of concentration in order to optimize grinding and forecast losses of metals along with tailings were reported by W. Petruk (Canada) at the XX International Mineral Processing Congress in 1997. The results obtained allowed Petruk not only to recommend a two-stage scheme of grinding but also to reveal an isomorphic admixture of silver in galena. The implementation of the new technology provided an increase in Pb recovery by 5%.

The rapid forecasting of the dressability of chromite ore using image analysis in combination with microprobe measurements allowed A. Tasdemir (Turkey) to develop a technique of piece-by-piece sorting of ore with production of conditioned concentrates at a prime cost 1.5 times lower.

In Russia, the Videomaster-56 system has been created for automatic geometrical optical image analysis. The technical parameters of this system are not worse than those of first-class analyzers, whereas the more developed software support enables one to obtain results unattainable for previously designed and more specialized systems of image analysis.

Recent investigations of the dressability of various ore types showed rather reliable work of the analyzing systems and adequate results obtained at different stages of geological exploration and development of mineral deposits. These results provide a basis for estimation of the expediency of deposit development and technological assessment of natural and technogenic mineral resources and products of concentration at operating mining and concentrating plants. In other words, this method may be used for estimation of mineral resources at all stages from geological exploration of deposits to finished products.

Image analysis has not been so widely applied abroad, and Russian scientists are the leaders in this research. It is evident that, in the near future, this method will be widespread in estimation of mineral resources in our country and worldwide. A special section on image analysis was included in the program of the XXI International Mineral Processing Congress (Rome, 2000).

Main scientific results. (1) The composition, depth of penetration, and character of distribution of surficial compounds on natural diamonds in the process of their interaction with industrial water during concentration of diamond-bearing kimberlite were studied with X-ray photoelectron spectroscopy, Auger spectroscopy, and image analysis by V.A. Chanturiya from the Research Institute of Comprehensive Exploitation of Mineral Resources (IPKON), Russian Academy of Sciences (RAS), and Yu.P. Dikov from the Institute of Geology

of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM), RAS.

(2) A forecasting map of the dressability of high-sulfur coal in the Rostov region was compiled based on image analysis and a technology of deep concentration of coal was elaborated to produce concentrate with <12% ash and <3% S by V.A. Chanturiya, K.N. Trubetskoi, and G.D. Krasnov from IPKON and T.V. Bashlykova from the Moscow Institute of Steel and Alloys (MISS).

(3) The interrelations of the morphometric parameters of the major minerals from some gold, manganese, and iron deposits of Russia and the conditions of opening of mineral complexes and additional recovery of gold from tailings were investigated by V.A. Chanturiya, IPKON; E.G. Ozhogina, the All-Russia Institute of Mineral Resources (VIMS); T.V. Bashlykova, MISS; and V.A. Zuev, the engineering company OAO Mekhanobr.

(4) A highly efficient and environmentally safe technology of concentration of manganese ore at the Porozhinsky deposit was worked out by E.G. Ozhogina from VIMS on the basis of image analysis.

Expected scientific and applied results. (1) The use of image analysis will enable study of the phase transformations of disseminated sulfide and gangue minerals in the process of their storage in tailing dumps. The results obtained can serve as a basis for assessment of the possible involvement of these dumps in processing taking into account technological, economic, and environmental criteria.

(2) A system of certification of minerals and a unified electronic library of certificates of materials supplied for processing and technological products of processing will be developed in order to ensure rational subsurface management and resource conservation on the basis of automated systems of information and analytical support of decisions on regional development of mineral resources.

(3) The efficiency of research in this field is determined in many respects by equipment of analyzing systems with modern high-resolution optical devices for the study of solids.

*Scientific Substantiation and Development
of Alternative Processes of Intergranular
Disintegration of Mineral Complexes, Enhancement
of Contrast in Mineral Properties,
and Opening of Refractory Ore*

As follows from available data, 35–40% of losses in the course of primary processing are related to mineral intergrowths and 30–35%, to fine particles smaller than 40 μm in size. To decrease these losses and the energy consumption for grinding ore, it is necessary to replace traditional unselective grinding by selective disintegration. Such possibilities arise when energy effects (electrochemical effects, microwave processing, impacts of accelerated electrons and powerful electromagnetic

pulses) are used in the process of ore processing, flotation, and leaching.

The study of various energy effects on semiconductor (sulfides) and dielectric (quartz, calcite, etc.) minerals shows that microfractures arise at mineral boundaries within intergrowths, disruption channels appear within particular grains, and new phases are formed at the surface of sulfides. These effects sharply decrease energy consumption for ore disintegration and enhance the selectivity of disintegration of mineral complexes and opening of Au-bearing sulfides and the contrast in mineral properties. The new knowledge opens up fresh opportunities for separating mineral components and increasing the efficiency of traditional processes related to concentration of mineral resources and hydrometallurgy.

A great deal of publications on application of alternative energy methods of mineral processing have appeared over the last decade.

W. Trahar (Australia) investigated mechanisms of compound formation at the surface of galena and chalcopyrite in the process of electrochemical polarization of sulfides and proved the possibility of efficiently separating them and obtaining high-quality concentrates without using flotation reagents.

R. Bertram (Germany) provided insights into the mechanism of electrochemical dissolution of sulfides and proposed optimal regimes of leaching on the basis of anode dissolution of copper sulfides in sulfuric acid solutions and phase changes at the surfaces of chalcocite, covellite, and chalcopyrite.

P. Richardson (United States), in his report at the XX International Mineral Processing Congress, provided evidence for the efficiency of electrochemical polarization of sulfide ore in the process of its grinding. A diminished consumption of grinding bodies by 30% was achieved owing to the creation of a reducing medium in the mill and a decrease in the oxygen concentration (cathode treatment of the pulp). It should be noted that similar studies were carried out in Russia 15 years ago by V.A. Chanturiya from IPKON and E.L. Chanturiya from VIMS.

A comparison of Russian and foreign investigations shows that Russian scientists have advanced farther in understanding the mechanism of disintegration and opening of refractory ore and increase in the contrast of mineral properties based on use of electrochemical effects, the energy of accelerated electrons, and powerful electromagnetic pulses during failure of rocks and mineral complexes. This situation is probably due to the leadership of Russian physicists in the theory and practical use of powerful energy effects for industrial and military purposes.

Foreign publications are focused largely on electrochemical and microwave methods of intensification of primary mineral processing.

At the XXIII International Mineral Processing Congress (Turkey, 2006), these technologies were characterized as technologies of the 21st century.

Main scientific results. (1) Insights were provided into the effects of the energy of accelerated electrons on mechanical, sorption, electrochemical, flotation, and magnetic properties of sulfides and iron minerals. The relationships between the aforementioned properties of minerals and the energy and dose of irradiation were established (V.A. Chanturiya, IPKON, and G.R. Bochkarev, Mining Institute, Siberian Division, RAS).

(2) The loss of strength of mineral aggregates owing to leaching and formation of new phases and microfractures in the sulfide lattice was established from study of the morphometric, physicochemical, and structural properties of Au-bearing sulfide suspensions affected by a direct current. As a result, the permeability of solutions increased by two to six times (T.V. Chekushina and A.V. Zubenko, IPKON).

(3) It was ascertained that the effect of powerful electromagnetic pulses on opening of Au-bearing sulfides consists in development of a network of disruption channels within sulfide grains. This network provides access of the solution to gold and silver. The recovery of noble metals increases by 20%, while energy consumption decreases by two to three times in comparison with traditional methods. This approach allows development of a new, highly efficient energy-saving technology of ore processing that shortens the way from raw material to final products (V.A. Chanturiya, I.Zh. Bunin, and V.D. Lunin, IPKON; Yu.V. Gulyaev and V.A. Cherepenin, Institute of Radio Engineering and Electronics, RAS; G.V. Sedel'nikova, Central Institute of Geological Exploration for Base and Precious Metals (TsNIGRI)).

(4) The scientific principles and a technology of activation of hydrophile diamonds with anolyte solution were elaborated. The removal of Fe, Mg, and Si from the diamond surface provides a 1.3- to 3.0-fold decrease in the concentration of these elements in the surficial layer of diamonds. The thinned film enhances the hydrophobicity and flotation ability of diamonds (V.A. Chanturiya and E.A. Trofimova, IPKON, and Yu.P. Dikov, IGEM).

(5) The mechanism of disintegration of ore in an apparatus that provides volumetric failure in a layer of particles has been established. This mechanism diminishes energy consumption for ore processing by 40–60% (I.I. Blekhman, OAO Mekhanobr; P.K. Fedotov, Irkutsk State Technical University).

Expected scientific and applied results. (1) A theoretical basis will be created for application of energy effects to various types of minerals and different stages of their processing. New, highly efficient and energy-saving technology and equipment for disintegration and opening of refractory ores in the course of their grinding and hydrometallurgical processing will be developed.

(2) The use of fractal analysis will enable the parametric representation of disordered structures of defects at the surface of sulfides and the quantitative assessment of the implications of defect structure for

the electrical properties and hydrophobicity of minerals. This information will make possible the scientifically supported application of various energy effects to directed change of the surface and technological properties of sulfides.

(3) With the advance of new fields in high-energy physics, it will be possible to use laser and electronic, ionic, and plasma technologies for recovery of valuable components from ore.

The efficient solution of this problem depends in many respects on outfitting of laboratories with modern scientific instrumentation, computing equipment, and analytical devices.

New Environmentally Safe Comprehensive Processing of Refractory Ores Based on Combination of Efficient Concentration Methods with Pyro- and Hydrometallurgy

Concentration is the separation of minerals without a change in their phase and chemical compositions. Concentration becomes powerless in processing of ore consisting of submicron particles. The main contradiction between the current status of mineral resources and the traditional technology of their primary processing is the necessity to involve in mining ores and technogenic minerals such that they cannot be separated into mineral phases and thus cannot be concentrated.

The most radical solution to this problem is processing ores and technogenic minerals at mining and metallurgical integrated works, where only the easily concentrated portion of valuable components is recovered into concentrates, while unopened mineral aggregates are directed to the metallurgical cycle. The combination of pyro- and hydrometallurgical procedures intended for processing of low-grade ore with concentration provides for the comprehensive recovery of metals or chemical compounds and utilization of minerals.

Basic investigations in this area enable development of rational combined technologies for different types of mineral materials based on study of the interaction of minerals with chemical solvents and the fusion of concentrates in various thermal regimes.

The implementation of these technologies will enhance the efficiency of mining and metallurgical processing and increase available mineral resources due to use of low-grade and refractory ores.

Extensive experimental data on use of pyro- and hydrometallurgy for processing base-metal, uranium, and rare-metal ores have been accumulated to date. The bioleaching of copper, zinc, noble metals, uranium, iron, fluorite, silicon, antimony, arsenic, and sulfur is a subject of current studies. The underground leaching of uranium and multicomponent ores with subsequent sorption-extraction recovery of U, Mo, Re, V, Se, Sc, and REE is widely used in Russia.

F. Habashi (Canada) performed a comprehensive study on the mechanism of leaching and sorption-

extraction recovery of valuable components from Cu, Au, Hg, Ni, U, and Zn ores. Habashi considered the possibility of obtaining alumina from non-bauxite ore and synthetic rutile from ilmenite, processing of ferromanganese nodules taken from the seafloor, and desulfurization of coal. The autoclave leaching of base-metal concentrates has been introduced at the Sherif Gordon works.

D. Miller (United States) carried out a comprehensive study on autoclave leaching of gravity and flotation concentrates of refractory Au-bearing ore with subsequent cyanide leaching and electrolytic recovery of gold from solution. The combined technology has been successfully realized at some enterprises. The heap leaching of oxidized copper and low-grade Au-bearing ores is being actively implemented.

The considerable theoretical and experimental experience with regard to sorption-extraction leaching made possible the introduction of combined technologies at some enterprises in Russia.

Main scientific results. (1) A theory and technology of sorption-extraction recovery of U, Mo, Re, V, Se, Sc, Y, and REE from the solutions obtained as a result of processing of uranium and multicomponent ores were elaborated by N.P. Laverov (IGEM), Yu.V. Nesterov (Atomredmetzoloto), and V.V. Shatalov (All-Russia Research Institute of Chemical Technology).

(2) Many insights were obtained into the mechanism of bioleaching of concentrates of refractory Au-bearing ore and use of iodine- and bromine-bearing reagents as low-toxicity solvents for noble metals. A combined, environmentally safe technology of vat and heap leaching of Au-bearing ore was elaborated (G.V. Sedel'nikova, TsNIGRI; E.V. Adamov, MISS).

(3) The scientific principles and combined concentration-hydrometallurgical technologies of comprehensive processing of finely disseminated base-metal and copper-nickel ores of complex compositions were worked out by V.V. Belikov from OAO Mekhanobr and M.Ya. Mantsevich from the State Research Institute of Nonferrous Metals.

Expected scientific and applied results. (1) The elaboration of scientific principles and technologies aimed at intensifying underground and heap leaching of valuable components from refractory ores with use of energy effects.

(2) The theoretical substantiation and experimental corroboration of combined technologies of comprehensive recovery of valuable components from natural mineralized water and mine drainage.

Elaboration of a Theory and Technology of Processing of Technogenic Minerals and New Methods of Water and Gas Conditioning

Millions of tons of valuable components can be found in mining and tailing dumps. The involvement of wastes in industrial processing expands available min-

eral resources and diminishes environmental loading on mining districts. Technogenic materials cannot be processed with traditional technologies because of variable physical and physicochemical properties of their components owing to oxidation, leaching, redeposition, and other processes that accompany mining and long-term storage in dumps. The scientific and technological investigations regarding processing of low-grade oxidized materials at technogenic deposits are related largely to the development of new, alternative technologies that combine concentration and hydrometallurgy. Highly efficient and environmentally safe methods of bleaching and purification of industrial water and mining drainage are being elaborated in order to create closed water circulation with additional recovery of valuable components and improvement of the environment. The development of a theoretical basis and the choice of general approaches to processing of mineral materials at technogenic deposits are crucial for elaboration of modern technologies based on comprehensive study of the physicochemical and technological properties of polycomponent water-mineral systems.

Despite a great number of recent publications, the general level of research in this field worldwide is not high due to the diversity of technogenic materials, difficulties related to their investigation, and needs for alternative combined technologies. The following important results that have found wide application should be mentioned.

A group of researchers from the United States elaborated hydrometallurgical techniques of processing low-grade Au-bearing products and tailings.

P. Baláž (Slovakia), based on the study of the dissolution kinetics of finely ground mineral components, provided insights into the mechanism and regimes of mechanochemical activation of technogenic materials for subsequent hydrometallurgical processing.

Y. Attila (United States) and J. Laskowsky (Canada) investigated the action of polymer flocculants during processing of various technogenic materials and demonstrated the possibility of their application to processing of coal sludge and Mo-bearing products.

Russian science may occupy a leading position in this field of research because of the diversity and economic value of the technogenic deposits of Russia and the significant scientific potential of the specialists working in this area.

In the near future, Russian scientists may exert a substantial influence on the advance of knowledge pertaining to this problem, first of all, as concerns the combined concentrating-metallurgical processing of technogenic materials and the development of the theoretical principles of flotation and coagulation of fine particles.

Main scientific results. (1) The scientific principles of the combined concentrating-metallurgical technology of processing tailings of Cu-Zn ore were elaborated on the basis of comprehensive study of the vari-

able character of the surface of ore minerals by V.A. Bocharov, MISS; V.E. Vigderhaus, IPKON; and V.D. Makarov, Institute of Chemistry and Technology of Rare Earth Elements and Mineral Resources (IKhTREMS), Kola Scientific Center (KSC), RAS.

(2) The theoretical grounds and scientific principles of pneumatic pulsatory flotation, which allows processing of finely dispersed minerals, were stated by G.D. Krasnov (IPKON).

(3) The scientific principles and a technology of processing of rare-metal and diamond-bearing products under conditions of closed water circulation were elaborated by V.A. Chanturiya, E.A. Trofimova, and G.P. Dvoichenkova (IPKON) and E.L. Chanturiya (VIMS) on the basis of development of an environmentally safe electrochemical technology of water processing.

(4) The oxidation of sulfides stored in tailing dumps for a long time was modeled by V.D. Makarov (IKhTREMS, KSC, RAS), who also assessed the optimal conditions of sulfide recovery with flotation.

Expected scientific and applied results. (1) A resource-saving combined scheme of sludge processing will be elaborated on the basis of theoretical and experimental modeling of aggregation and disintegration of finely dispersed floccules under the effects of coagulants and dispersants.

(2) The development of the theoretical principles of bubble mineralization will lead to optimization of flotation separation and extend the range of application of the flotation technique to concentration of oxidized and finely dispersed minerals.

(3) Future combined technologies of technogenic waste processing will include preparation of refractory material by means of various energy effects, concentration, leaching, and sorption.

(4) Resource-saving technologies of water processing and utilization of industrial water will be based on new efficient sorbents and bioflocculants, electrochemical treatment, and concentration of diluted solutions.

CONCLUSIONS

At present, Russia has efficient energy-saving technologies of complex ore processing that correspond to the world level and even exceed it in some cases, as was repeatedly pointed out at recent sessions of the International Mineral Processing Congress.

The implementation of new technologies at mining and concentrating enterprises of Russia will make it possible to increase the recovery of metals by 10–15% while obtaining high-quality concentrates competitive on the world market; lower energy consumption; raise labor productivity by two to three times; involve subeconomic ore and technogenic materials in processing; fill a deficiency in manganese and rare and some other metals; and finally, substantially improve the environment in mining districts.

Further development of methods of primary mineral processing should be grounded on basic research in the field of mineral separation. The main lines of scientific progress in primary processing of natural minerals and technogenic materials require (1) study of the relationships of the structure and chemical and phase compositions of these minerals and materials with their physical, physicochemical, and technological properties; (2) combination of physicochemical modeling of mineral separation with experimental studies of concentration; and (3) elaboration of a theory of intergranular

disintegration of mineral complexes and a mechanism of vigorous opening of refractory ores and technogenic materials.

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