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Processing of Iron-Ore Waste from Enrichment Plants

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Abstract—Existing processing technologies for iron-ore wastes are analyzed. For the Kemorovo region, it makes sense to employ a processing technology with products corresponding to local requirements. Effective technologies may be combined to meet the full set of requirements. The formulation of waste-processing options is considered. Various proposals are developed for stepwise processing of iron-ore wastes, with the extraction of useful components by chemical methods, restoration of the damaged landscape, and the creation of recreation areas on the reclaimed land. Recommendations are developed for year-round processing of iron-ore wastes by chemical methods, even in winter. Maps are presented for the processing of ore tailings, with stepwise restoration of the reclaimed land. The number of stages selected will depend on the investment required and the annual throughput of the waste-processing system, with the possibility of simultaneous restoration of several sections. After complete removal of the iron-ore wastes from the tailings stores, preparations begin for the development of recreation areas: offers are solicited for the design of the recreation zones, the dismantling and sale of equipment, buildings, and other structures, the restoration of the ground cover, laying of turf, and planting of trees and shrubs. Restoration of the territory may run in parallel with processing of the waste. The recreation areas go into operation after the elimination of the waste. Scilab software is used for mathematical simulation of the waste-processing proposals for the Kemerovo region, with evaluation of its effectiveness in the following terms: economic benefit; restoration of damaged land; pollutant burden; population of the affected regions with standard socioeconomic indices; and prevention of public-health impairments. By graphical means, the Pareto-optimal solutions are selected from among the various proposals. The best Pareto-optimal solutions are selected on the basis of ranking in terms of public health and environmental safety (low, moderate, and high) in the Kemerovo region.

Keywords: integrated technologies, remediation proposals, public health, environmental safety, waste processing, natural resources, resource management, iron-ore tailings, computer modeling

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In the Kemerovo region, there are copious tailings from iron-ore extraction, which represent a hazard to public health and to the environment [1, 2]. Besides barren rock, the tailings also contain tons of gold, tens of tons of silver, and hundreds of thousands of tons of iron. Therefore, the tailings may expediently be regarded as valuable resources. However, their further expansion may precipitate an environmental catastrophe in the region.

Iron-ore wastes are stored in tailings facilities equipped with pumping stations that recycle water. As a rule, the wastes are stored within 5 km of the processing plant. The storage facilities are based on a natural compact clay layer, which prevents the escape of tailings to the soil and groundwater. The iron content in the wastes is more than 15%; about 3% is magnetite, while around 2–4% consists of pyrite [1].

Analysis of the best available technologies indicates that the main approaches are mechanical, gravitational, flotational, chemical, and magnetic enrichment (Table 1) [3–8].

In the Kemerovo region, gravitational methods are ineffective, since the useful components and the rock do not differ greatly in density. Flotation requires large capital investments and is based on hydrophilic and hydrophobic properties of the particles. On account of the high sulfur content in the tailings, this approach is economically and environmentally inadvisable. Chemical processing permits the extraction of useful components such as iron from pyrite [14, 16]. That significantly decreases the sulfur content in the iron concentrate. Thus, the product obtained from the waste will meet the requirements of the steel industry and other users.

Waste-free processing technologies for iron-ore tailings may be selected and combined for optimal resource management on the basis of the principles for the maintenance of public health and environmental safety developed in [17].

Table 1. Processing and utilization of iron-ore wastes

Technology	Sources of waste
Production of brick and building materials [9]	Rock overburden from mines, rock wastes from enrichment
Production of porous fillers as additives in concrete and cement production [9]	Crushed rock from mining and enrichment
Construction of highways, industrial parks, embankments, and other structures [10]	Rock overburden from mines, rock wastes from enrichment
Production of fertilizers [11, 12]	Wastes from mining and enrichment
Use in hydraulic structures (as packing in dams, as filters and sorbents) [11, 12]	Rock overburden from mines, rock wastes from enrichment
Extraction of rare-earth metals by flotational [13], magnetic, hydrometallurgical, chemical, and bacterial methods [11, 14, 15]	Wastes from mining and enrichment
Mechanized mining of the ore, allowing rock to be left in situ or moved to worked-out mine shafts [11, 12]	All rock or the rock stored in worked-out mineshafts as filler

Within that framework, we may develop a mathematical approach to the formulation of proposals for waste-processing, as follows.

The goal is to specify a list of j options ($j \in [1; J]$) for the development of the iron-ore wastes and the restoration of the land currently occupied by the waste. Each option is characterized by a set of technologies $Th(j)$ and characteristics $F(j) = \{F_1(j),\ l \in [1; L]\}$. When $L = 5$, these characteristics are the economic impact F_1; the area of land to be restored F_2; the pollutant burden as a result of ore enrichment F_3; the population of the region with standard socioeconomic indices F_4; and the prevention of public-health impairments F_5.

We need to formulate a set of proposals A_n ($n \in [1; N]$) for waste processing, with the development of recreation areas on the reclaimed land, on the basis of the set of j options ($j \in [1; J]$) so as to reduce the negative impact of production, in accordance with the standard characteristics $\{F_1^*\}$

$$\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{i=1}^{I} Cp_{tmni} \to \min \text{ when } A_n = \bigcup_{j=1}^{J} Th(j)$$

under the conditions

$$\begin{gathered} F_1^*(A) < F_1(A);\ F_2^*(A) < F_2(A); \\ F_3^*(A) < F_3(A); F_4^*(A) < F_4(A); \\ F_5^*(A) < F_5(A), \end{gathered} \qquad (1)$$

where Cp are the capital costs for the introduction of the waste-free technologies, rub.

We now develop a procedure for formulating and combining waste-processing proposals [17]. Table 2 summarizes the proposals for the processing of iron-ore wastes from Kemerovo enrichment facilities.

The proposals are intended to reach their design capacity by 2020, with restoration of the reclaimed territory in stages from 2020 and the creation of recreation areas (green space) from 2031.

In view of the characteristics and location of the ore tailings from iron-ore enrichment in the Kemerovo region, year-round extraction of useful components from the waste by heap leaching is considered. A weak sulfuric-acid (H_2SO_4) solution is added to the tailings. In winter, the irrigation line is covered by a 2-m ore layer for insulation from the low temperatures [14, 16].

Since the tailings are remote from the plant and the climate in the Kemerovo region is challenging, transportation of the solution with the useful components by pipeline to the plant is recommended, for further reduction and drying [18].

The system for reduction and deposition of the useful components extracted from the enrichment tailings may expediently be located in the plant's enrichment shop. After drying out the solution (by means of existing equipment), the rock residue may be used as mineral additives to asphalt concrete and as ground cover for construction purposes. If there is no demand for construction materials, the waste, after extraction of the useful components, may be remediated by planting trees and bushes.

The procedure adopted in dealing with the tailings is as follows (Fig. 1). The tailings dump is divided into sections: the number and size of the sections will depend on the available financial resources and the throughput of the processing facility. In the first stage, attention focuses on the first section: the wastes are removed and the reclaimed land is restored.

In the subsequent stages, after complete removal of the wastes, preparations are made for the creation of recreation areas. Depending on the available financial resources and the throughput of the processing facility, several sections of the tailings store may be

Table 2. Proposals for processing iron-ore wastes (up to 2035)

Proposal	Characteristics
1. Construction (2017–2018) and introduction (2019) of a waste-processing system with the production of construction materials (packing for roadways, embankments, dams, etc.)	Waste throughput 0.7×10^6 t/yr (100 t/h). Investment 30×10^6 rub
2. Construction (2017–2018) and introduction (2019) of a waste-processing system with the production of 60–62% iron-ore concentrate by heap leaching with sulfuric acid	Waste throughput 0.7×10^6 t/yr (100 t/h). Investment 64×10^6 rub. Concentrate output 60000 t/yr
3. Construction (2017–2018) and introduction (2019) of a waste-processing system with the production of 60–62% iron-ore concentrate by biological leaching with thionic bacteria	Waste throughput 0.7×10^6 t/yr (100 t/h). Investment 54×10^6 rub. Concentrate output 60000 t/yr
4. Construction (2017–2018) and introduction (2019) of a waste-processing system with the production of 60% gold-ore concentrate by biological leaching with thionic bacteria	Waste throughput 0.7×10^6 t/yr (100 t/h). Investment 60×10^6 rub. Concentrate output 40 kg/yr
5. Construction (2017–2018) and introduction (2019) of a waste-processing system with the production of 65–70% gold-ore concentrate by heap leaching with sulfuric acid	Waste throughput 0.7×10^6 t/yr (100 t/h). Investment 96×10^6 rub. Concentrate output 48 kg/yr
6. Construction (2017–2018) and introduction (2019) of a waste-processing system with the production of 65% copper concentrate by biological leaching with thionic bacteria	Waste throughput 0.7×10^6 t/yr (100 t/h). Investment 96×10^6 rub. Concentrate output 56 t/yr
7. Construction (2017–2018) and introduction (2019) of a waste-processing system with the production of 65% silver concentrate by biological leaching with thionic bacteria	Waste throughput 0.7×10^6 t/yr (100 t/h). Investment 60×10^6 rub. Concentrate output 80 kg/yr

worked at the same time: for example, the first and last sections.

After the wastes have been completely removed from the whole tailings dump (stage $n - 5$), offers for the design of the recreation areas are solicited. The preparations for the creation of the recreation areas (stages from $n - 5$ to n) involve selection of the design for the recreation areas; dismantling and sale of the equipment; dismantling (or modernization) of the buildings; restoration of the ground cover; laying of turf; and planting of trees and shrubs. Restoration of the territory runs in parallel with processing of the waste. The recreation areas go into operation after shutdown of the processing enterprise (step n).

Scilab software is used for mathematical simulation of the waste-processing proposals. Five models relating to aspects of public health and environmental safety are employed: economics (F_1), environment (F_2), environmental impact of production (F_3), social impact (F_4), and harm prevention (F_5) [19]. The results of the model experiments are presented in Fig. 2.

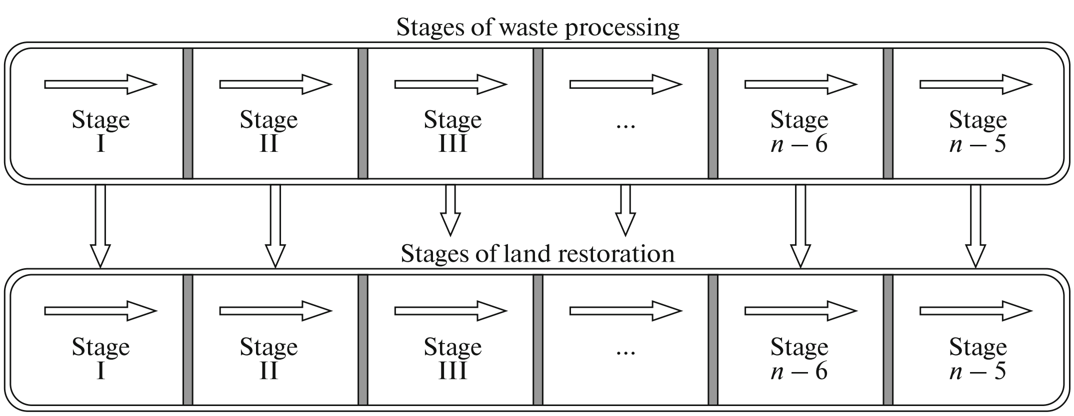

Fig. 1. Maps of tailings processing.

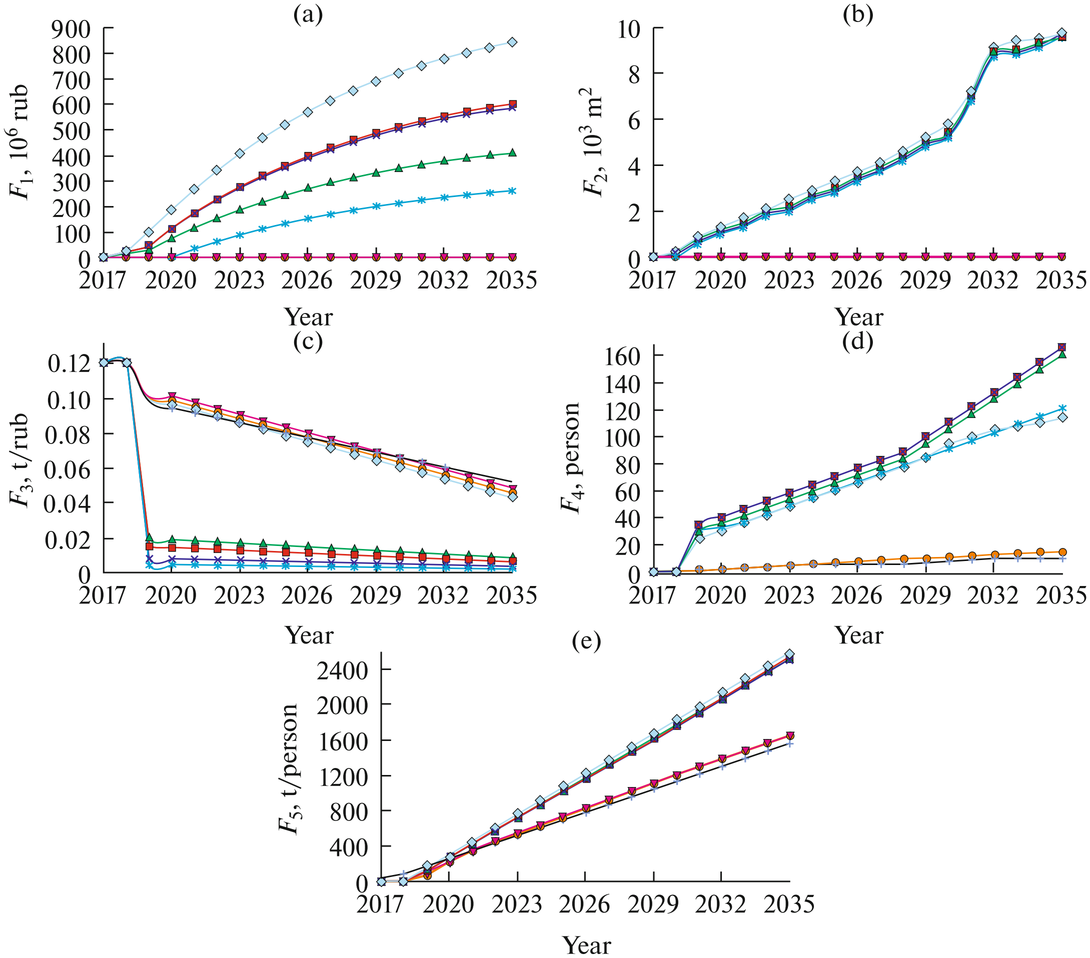

Fig. 2. Modeling results for processing of iron-ore wastes in the Kemerovo region according to proposals 1 (◇), 2 (■), 3 (▲), 4 (×), 5 (✱), 6 (●), and 7 (▼). The limit (+) is also shown.

Table 3 presents the expected consequences of waste-processing proposals 1–7. By graphical means, the Pareto-optimal solutions are selected from among the proposals in Table 2 (Fig. 3) [20]. The optimization is based primarily on the economic impact (F_1), the restored land area (F_2), and the population of the affected regions with standard socioeconomic indices (F_4). The pollutant burden (F_3) and prevention of public-health impairments (F_5) are adopted as constraints.

Proposals 1, 2, and 4 are Pareto-optimal. The best of these are selected on the basis of ranking in terms of public health and environmental safety (low, moderate, and high) in the Kemerovo region. The boundar-

Table 3. Evaluation of waste-processing proposals

Proposal	F_1, 10^6 rub	F_2, 10^3 m^2	F_3, t/rub	F_4, person	F_5, t/person
1	841.02	9.6500	0.043	114	2587.0
2	601.50	9.5000	0.006	166	2547.0
3	412.11	9.5000	0.009	161	2524.9
4	590.50	9.7000	0.003	164	2516.9
5	263.00	9.3000	0.002	121	2501.9
6	5.00	0.0001	0.045	15	1645.2
7	2.00	0.0001	0.048	10	1656.2

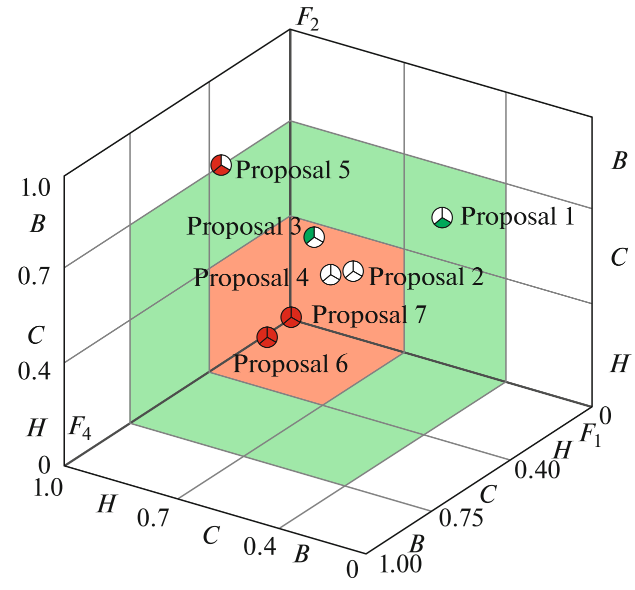

Fig. 3. Determination of the Pareto-optimal set of proposals for the processing of iron-ore waste.

ies between low and moderate and between moderate and high are determined on the basis of expert opinions. Proposals 2 and 4 are of rank 1.

CONCLUSIONS

Analysis of processing technologies for iron-ore wastes permits the formulation of proposals for the elimination of the public-health and environmental impacts of ore-enrichment facilities in mining regions.

By mathematical modeling, the interests of mine owners, regional government, and investors may be reconciled.

This approach permits an integrated approach to stage-by-stage waste processing, restoration of the reclaimed land, and the development of recreation areas, with decrease in the economic and environmental costs of ore processing. Thus, by this means, waste-free processing technologies for iron-ore tailings may be selected and combined for optimal resource management on the basis of rational principles for the maintenance of public health and environmental safety.

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