PROPHYLACTIC APPROACH TO SOLVING ENVIRONMENTAL PROBLEMS OF THE MINING INDUSTRY IN LINKAGE WITH ENERGY CONSUMPTION

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ABSTRACT. Existing technologies for developing ore deposits lead to irrational energy costs for delivering empty rock as part of the ore to the surface, while the content of the target component in the extracted raw material can be hundredths of a percent, not to mention the environmental damage from placing dump waste in the open air. A process of underground processing of rock mass is proposed, based on grinding of ore in an artificial liquid with intermediate density between the target and waste components. Herewith ballast minerals are automatically freed from intergrowths with valuable components by floating up during milling. This prevents the irrational expenditure of most of the energy on unjustified grinding of the main constituent of ore. As a result of the proposed treatment, when mining ores of most metals, the weight of the rock mass brought to the surface decreases by 7...10 times, whereas when mining gold, this reduction can reach hundred-fold. Thus, the reduction of the volume of cargo lifted onto the earth's surface is the second factor in reducing energy costs in mining.

Key words: interaction of the mining industry with the environment, methods of ore-dressing, underground conditions.

Introduction

Metals are essential for the sustainable development of modern society owing to their unique properties and wide range of applications. They are crucial for our everyday life and high technologies development. Construction and transportation, infrastructure, electronics, communications and space technologies, and many other areas need metals. The increasing global population and rising living standards drive a growing demand for metals (Watari et al., 2021). Even some metals are included in lists of critical raw materials (European Commission, 2023; Klochko, 2024).

Mining of ores and extraction of metals from them is one of the basic conditions for the successful functioning of modern civilization.

The steady growth in the demand for metal products stimulates the rapid development of the mining industry and metallurgy.

However, as readily available metal resources are exhausted, reliance on traditional approaches to the development of metallurgical raw material deposits leads to a disproportionate increase in energy costs and an exacerbation of the conflict between the mining industry and the environment.

The continuous operation of the world mining industry on a traditional technological basis led to an aggravation of the main contradiction of mineral deposit being developed, when the entire volume of the mining mass is brought to the surface while the content of the target component in the original ore may be fractions of a percent. As a result, huge volumes of mined-out space are formed underground (Bondarenko et al., 2012). Over time, they lead to irreversible intensive development of geomechanical processes of displacement of overlying rocks and, as a consequence, to irreparable damage to all natural and man-made surface objects due to subsidence of the earth's surface (Marian and Onica, 2021; Mononen et al., 2022), not to mention the direct withdrawal of agricultural arable land for the placement of unutilized enrichment waste (Bouaziz, and Benndorf, 2024).

The development of the global mining industry is characterised by a steady accretion of three main trends:

- Steady reduction in the content of valuable components in the extracted raw materials;
- Unbridled growth in the production capacity of mines in terms of the volume of mineral extraction.
- Continuous growth of the depths at which underground mining is carried out.

It is clear that the first two trends are organically interconnected: the lower the content of the target component of the ore, the more ore is required to be mined to produce the same volume of pure metal.

The changes taking place in mining can be illustrated by the exponentially declining curve - Figure 1 (Starostin, 2001):

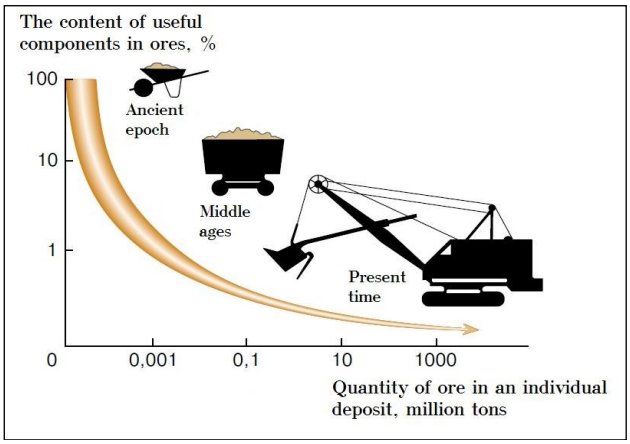


Fig. 1. Relation between the quantity of mined out ores and their useful components content (Starostin, 2001)

For example, chrysocolla (Eilat stone, copper ore) was mined at one of the oldest copper mines in the world, King Solomon's Mines (in the Timna region, modern Israel) using underground methods back in the days of the Egyptian pharaohs, i.e., about 3 thousand years ago BC, at a depth of 15...40 meters from the ground in volumes amounting to tens of tons per year. The copper content in the ore, produced in those ancient times, was higher than 20%, and sometimes came up to 98 - 99% - which means that this was not ore, this was native

copper. Nowadays, the copper content in the vast majority of copper deposits in the world is 1.0 - 2.5% (Brodt and Zhikhor, 2013).

The ore grade decline is a significant challenge in resource extraction. Low concentrations of valuable components in extracted raw materials can lead to increased costs, energy consumption, and negative environmental impact in the extraction and processing stages. This can also create challenges in ensuring a secure and sustainable supply of resources.

No less impressive is the increase in the depth of mineral extraction (Ghorbani et al., 2023). The annual rate of decline of the geodetic mark of mining operations is presented in Table 1 (Vakulov, 1999).

Table 1. *Increase in the depth of mineral extraction*

Size of the mine field along strike, km	Number of working horizons, units	The value of the annual decline of level, m/year
More than 2	1	5-15
	2	10-20
From 1 to 2	1	12-22
	2	15-25
From 0.6 to 1.0	1	15-27
	2	18-30
	3	20-40
	1	18-30
Less than 0.6	2	22-45

When developing steeply dipping ore bodies, the increase in mining depths takes on an extreme character – Table 2 (The Deepest Mines in the World).

Table 2. *Ten deepest mines in the world*

Mine name	Metal mined	Depth, m	Country
Mponeng Gold Mine	Au	4000	South Africa
TauTona Mine	Au	3900	South Africa
Savuka Gold Mine	Au	3700	South Africa
East Rand Mine	Au	3585	South Africa
Driefontein Mine	Au	3420	South Africa
Kusasalethu Mine	Au	3388	South Africa
Empire Mine	Au	3355	USA
Kloof Mine	Au	3347	South Africa
Blyvooruitzicht Mine	Au, U	3213	South Africa
Kolar Gold Fields	Au	3200	India

Mining at such extreme depths is accompanied by several difficulties: (i) need of cooling systems since the temperatures can reach up to 60°C; (ii) demanding strict safety measures since the miners face risks like rockfalls and seismic events; (iii) the deeper the mine, the more expensive it is to extract resources.

The phenomenally low content of the valuable component in the ore, combined with the record depth of extraction, leads to extremely low energy efficiency of such a mine, since the largest share of energy costs is spent on servicing the waste rock, and not at all on delivering the target ingredient to the earth's surface. The extremely unfavourable factors of conducting production activities in such extreme conditions give rise to both an aggravation of relations with the environment and a drop in the profitability of such a mine, which can lead to its bankruptcy. For example, South African platinum group metals (PGM) producer Impala Platinum (Implats) could close its Lac des Iles palladium mine in Canada earlier than planned (Argus Non-Ferrous Markets, 2025).

The crisis in the relationship between mining and the environment, which is worsening with the development of modern civilization, can be successfully overcome only by searching for more advanced technical solutions that allow for the enrichment of ore in underground conditions, which frees the earth's surface from the storage of dump rock on it and leads to the elimination of energy costs for the Sisyphean labour of lifting the ballast component of ore from the mine (Brodt and Sitko, 1988; Klein et al., 2002; Klein et al., 2003; Bamber et al. 2004; Hughes and Cormack, 2008, Hughes and Grig, 2008; Lane et al. 2008; Schropp et al., 2014; Baines et al. 2017).

Theoretical prerequisites

The analysis of possible methodological approaches to practical solution of the problem of developing such concentration process in underground conditions shows that it should not be based on artificial imparting of some differences in their properties for the minerals to be separated, as at is done at present on the earth's surface. For example, at the flotation separation of minerals, the surface of the component extracted into foam is preliminarily selectively hydrophobized by respective surface-active substances, while the surface of waste minerals remains hydrophilic. Instead, it should be aimed at the use of natural contrast in principal properties, which are parameters of the state of minerals that cannot be artificially corrected.

The only state parameter allowing an unmistakable and unambiguous identification of any mineral, which has been used in the concentration practice since long ago, is the natural density. Therefore, the most universal approach to the development of underground concentration processes can be the use of density difference of components to be separated, because one cannot find two individual minerals characterised, other conditions being the same, by identical densities. They can be easily separated in a true special liquid with strictly intermediate density of target and gangue minerals. However, until recently, it was impossible to prepare such a liquid at an acceptable price. Therefore, somewhat different, well-known gravitational methods of minerals concentration based on this principle were developed. They make use of their surrogate – magnetite or ferrosilicon suspensions – as artificial heavy media for target component separation from waste rock (Grobler et al., 2002; Gajda et al., 2018).

Meanwhile, it is impossible even theoretically to develop such highly efficient concentration process of target component extraction out of the ore in underground conditions on this basis, due to the fact that the solid phase in such suspensions is finely dispersed powder of a number of heavy minerals.

As the ore is crushed, its minerals become comparable in size to the solid phase forming the technological suspension.

As a result, it is not the suspension that acts as a continuous medium for the ore minerals, but the water itself. However, the

density of water is too low to "see" the difference in density between the minerals being separated.

On the other hand, the known grinding processes preceding gravitational separation are also far from being energetically and technologically perfect and can hardly be successfully used in underground conditions in their present-day form.

A way out is a natural combination of grinding process with separation process realized in a liquid whose density is strictly intermediate between those of minerals to be separated. Such a process can be accomplished in a conventional ball mill filled with such heavy liquid.

When the ore is fed to the mill, waste rock contained in the ground ore remains afloat in the heavy liquid and is not submerged into the zone of milling bodies impact. During the release of waste minerals out of the accretions with target component, this material, which does not need coarseness reduction any more, slips out of the impact of balls rolling in the mill, thus avoiding further destruction.

However, a necessary condition for the realization of such bi-functional processes is the availability of sufficiently cheap heavy liquids with a specified set of rheological, thermodynamic, hygiene and sanitary properties, which allow, besides, easy and low-power-consuming regeneration in underground conditions. At the same time, the limiting factor of the entire economy of such an enrichment process is the condition of 100% complete regeneration of such a heavy medium. Only in this case, the physiologically inert working agent of such an underground enrichment cycle is practically not consumed in such a compact, and at the same time, highly productive, separation process implemented in underground conditions, but is in a closed circuit of its circulation.

Accordingly, in addition to substantiating the most optimal formulations of working media for underground enrichment of ores, prepared on an aqueous (or non-aqueous, two-layer) basis, the main emphasis in the development of such highly economical and environmentally friendly technological processes was placed on the construction of fully closed and energy-efficient regeneration cycles of spent heavy liquids. Thus, unlike flotation reagents, their residues are not carried out with the enrichment products, but are almost completely returned to the head of the technological process.

A general classification of the entire array of possible heavy liquids for the design of such underground technological processes is given in Figure 2.

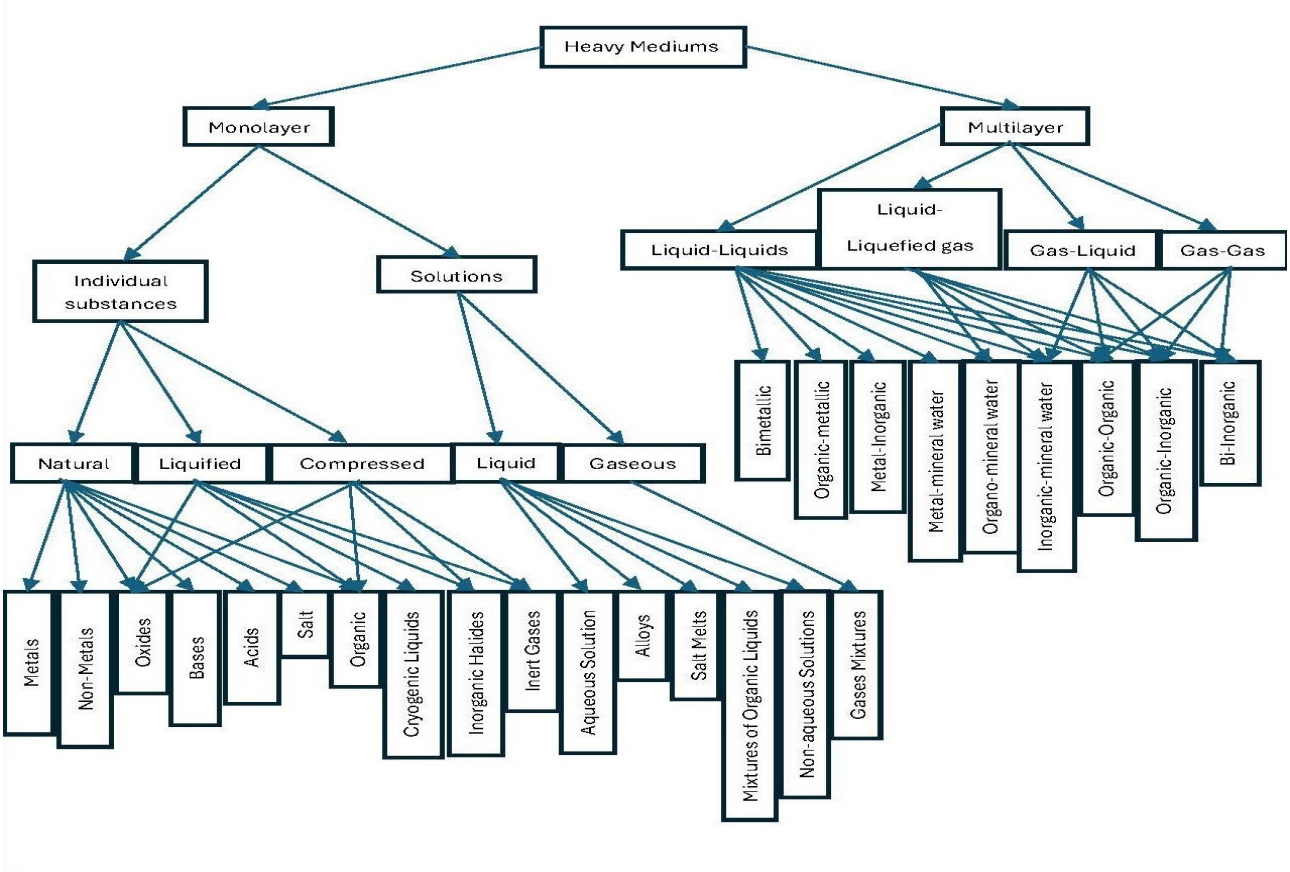


Fig. 2. Classification of possible heavy liquids that may be considered for the design of underground technological process based on minerals density difference

Materials and methods

The experiments were performed on ores samples collected from a number of deposits in the USA, Russia and South Africa. The exact data on deposits and ores are private property.

The media used in the studies were multi-component and prepared on a water basis specifically for ore enrichment.

Depending on the concentration of mineral salts included in them, the density of such liquids varied in the range of 2.70...2.90 g/cm^3.

Working with such media did not impose any additional requirements for sanitary working conditions, since only water vapour was present above their surface mirror.

The composition of these liquids is under patent issuing procedure.

The purpose of the preliminary laboratory experiments, conducted in a separatory funnel - Figure 3, was to predict the results of stratification of the ore minerals into concentrate and dump rock when contacting with suitable liquid.

The main part of the tests was carried out on a pilot plant equipped with a ball mill with a spiral classifier - Figure 4. The multi-component water-salt solution found as optimal in laboratory studies was used for pilot testing.

However, unlike traditional grinding systems using ball mills operating in a closed cycle with a spiral classifier, in this case the classifier worked as a gravity separator, raking ore concentrate from the bottom of the trough regardless of its size. The classifier spiral scooped out the concentrate from the bottom of the inclined trench, and the waste rock remained afloat in the drain, after which the separation products underwent a hydromechanical wringing procedure in a centrifuge. The last traces of this liquid were removed from their wet surface by washing, followed by concentration of the wash water and return of the regenerated liquid to the head of the process.



Fig 3. Stratification of ore minerals in the laboratory experiments



Fig 4. Pilot plant used in experiments

Results and discussion

The results of testing the process on various types of ores in a pilot format did not bring any unexpected surprises compared to the data obtained in experiments conducted under laboratory conditions.

However, the yield of separation products was largely determined by the final grinding size. Therefore, when preliminary unsatisfactory results of the process were obtained, the dump waste remaining afloat in the spiral classifier was returned back to the mill for additional grinding.

Analysis of the obtained data on the material balance of such a process indicates the direct feasibility of underground processing of ores, especially rare and precious metals, since most of the ballast (up to 90%) can be separated from the original raw material already in underground conditions - Tables 3 - 5.

Table 3. *Material balance of tungsten ore enrichment in a pilot format*

Parameter	%
Content of WO_3 in the original ore	0.795
Output of concentrate	12.35
Content of WO_3 in concentrate	6.02
Extraction in concentrate	93.1
Content of WO_3 in tailings	0.063
Output of tailings	87.65
Extraction in tailings	6.9

Table 4. *Material balance of tin ore enrichment in a pilot format*

Parameter	%
Content of tin in original ore	0.745
Output of concentrate	8.90
Content of tin in concentrate	7.55
Extraction in concentrate	90.14
Content of tin in tailings	0.0807
Output of tailings	91.10
Extraction in tailings	9.86

Table 5. *Material balance of gold-bearing ore enrichment in a pilot format*

Parameter, measuring unit	Value
Content of gold in original ore, g/t	3.5
Output of Au concentrate, %	0.97
Content of Au in concentrate, %	33.9
Extraction in concentrate, %	93.95
Content of Au in tailings, g/t	0.214
Output of tailings, %	99.03
Extraction in tailings, %	6.05

As can be seen from the results above (Tables 3 – 5), in all cases of grinding the initial ore in a liquid with an intermediate density between the valuable component and the dump rock, a gentle mode of processing the initial raw material is achieved, allowing the preliminary removal of most of the waste rock. The mass that would be brought to the surface can be considerably decreased – from 7-10-fold for non-precious metals to around 100 times for gold. Undoubtedly, these will reduce sharply the energy needed for the mining activity. For example, it is found that at an ore grade of 0.5, 0.4 and 0.3% mining from 300 m of depth results in an energy cost of 60, 127 and 447 MJ/kg to obtain a 30%+ copper concentrate from underground mines,

and 52, 95 and 255 MJ/kg for surface mines, respectively (Koppelaar and Koppelaar, 2016).

Liquids used to separate valuable components from the excavated ore can be regenerated. The regeneration method is determined by several factors, and, first of all, by the recipe of the working liquid.

When working with water-salt solutions, multi-stage counter-current water washing of enrichment products was used to remove the last remnants of the working medium from the surface of the enrichment products. Evaporation, ice freezing and ion exchange have been studied for concentrating wash waters to the original density.

When working with organic liquids, extraction with selective low-boiling solvents was used.

However, alternative regeneration methods that do not involve flushing have also been developed.

Conclusions

The increase in mining depths and decline in quality of the mined mineral ore dictate the need for finding new environmentally friendly and energetically efficient processes of ore enrichment that are easily executed in underground conditions.

In order to solve this problem, grinding of the initially crushed ore in an artificial liquid with an intermediate density between the target and waste components of the ore is proposed. This eliminates irrational energy costs for servicing the main part of the initial raw material, especially when developing poor deposits at great depths.

To implement such a process, a family of artificial liquids with a given set of physical and sanitary properties is proposed. These liquids are multicomponent solutions based on several inorganic heteropoly compounds with admixtures of inorganic halides. Compositions with the participation of halogenated organics were used as organic media.

The proposed method is successfully used to concentrate tungsten, tin and gold ores with valuable components extraction rate 93,1; 90,14 and 93,95 %, respectively. A simple and energy-efficient processes for their almost complete regeneration have been proposed.

Underground ore processing prevents environmental damages caused by storing ore enrichment waste on the earth's surface and eliminates irrational energy costs associated with servicing the ballast component of the original raw material.

In addition, the placement of waste rock from ore enrichment in underground conditions prevents the development of the process of shifting of overlying rocks, which prevents the subsidence of the earth's surface that causes damage to all above-ground objects.

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