Iron ore underground mining under the internal overburden dump at the PJSC “Northern GZK”

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Abstract. Deterioration of mining conditions at mining deposits by open pit methods (increased mining depths, reduced ore deposit thickness) leads to an increase in mining costs. In Ukraine, to reduce open pit mining costs, overburden is disposed in temporary internal dumps located directly in the open pit over the ore reserves. Reactivation of pit areas with the temporary internal overburden dump located on them results in a surge of mining operations and deterioration of technical and economic indicators. Increased energy consumption, a decrease in working site parameters, an increase in angles of open pit slopes and stripping lags lead to unprofitability of open pit mining. One of the solutions to the mentioned scientific and engineering problem involves combined mining of deposits by integrated open pit and underground mining operations. The combined open pit-underground mining method enables reducing mining costs and enhancing technical and economic indicators. The suggested schemes for opening reserves located under the internal overburden dump enhance technical and economic indicators of deposit mining through making the internal dump a permanent one. This allows further disposal of overburden into internal dumps. Implementation of scientific recommendations and technological solutions resulted from the research performed (exemplified by the deposit Hannivske, Ukraine) reduces the cost of ore by 1.33 USD/t. At the same time, the total cost of building an underground mine makes 16.4 M USD, which is 30% less than when applying traditional opening vertical shaft schemes.

1. Introduction

Hannivske deposit of ferruginous quartzites has been mined by open pit methods since 1963. The depth of the open pit reaches 252 m (the lower mark of the mining horizon is -120 m). The deposit is explored in detail to the depth of 300 m in the central and northern parts and 500 m in the southern part. According to the design, the width of the open pit is 1.4 km, the length is 7.2 km, the depth makes 300 m in the northern part and 450 m in the southern part. In 2020, the planned stripping ratio made 1.0 m³/t, the average one was 0.84 m³/t according to the data of the Northern GZK (ore mining and beneficiation plant) [1].
In terms of the geological structure complexity, the deposit is classified as group 2a (the southern part up to profile 28) and to group 1b (northwards of profile 28). The deposit is a northern continuation of the rocks of Kryvyi Rih iron ore basin [2–5]. The length of the explored part is 14.5 km; the length of the design contour of the open pit is about 8 km [1,6,7].

The productive thickness of the deposit is represented by ferruginous quartzites of the first ferruginous horizon. The horizon thickness varies from 300-500 m in the south to 180-250 m in the north. Country rocks (the footwall) consist of alumina-silicate schists of the first schistous horizon that overlap (the hanging wall) magnetite-silicate quartzites of the fourth ferruginous horizon (figure 1).

![Geological cross-section by profile 33+170 (5.1 – 5.2): 1 – 4 – magnetite-silicate quartzites (substandard hanging walls); 5 – the footwall (magnetite quartzites); 6 – the area of underlying rock oxidation; 7 – loose Cenozoic sediments; PR_{1S^{2}2s} – quartz-magnetite-biotite schists; PR_{1S^{1}1S} – quartz-biotite-cummingtonite schists; PR_{1S^{0}0s} – magnetite-biotite-cummingtonite quartzites; PR_{1SK_{3}} – quartz-biotite schists; PR_{1SK_{2}} – quartz-sericite schists; PR_{1SK_{1}} – mica quartzites.](image)

The dip of rocks at almost the north-south strike is mainly westwards at angles 40 degree to 90 degree. In the southern part, the dip of rocks is steeper than in the northern part. As for the material composition of the textural-structural features and technological properties, the first ferruginous horizon is divided into two bands of approximately equal thickness – the footwall and the hanging wall.

The footwall which is 150–300 m thick in the south and 60–80 m thick in the north is composed of magnetite, hematite-magnetite quartzites with silicates and to a lesser extent of silicate-magnetite and magnetite-silicate quartzites. The latter two varieties occur in the form of thin layers (up to 20-40 m) in the hanging wall of the first ferruginous horizon [1,8–10].

In accordance with the design and quality requirements, the cut-off value of the mass fraction of $Fe_{mag}$ in quartzites of the footwall is 16%. The balance reserves also include less than 10 m thick substandard layers ($Fe_{mag} < 16\%$). In fact, quartzites of the hanging wall (especially in its northern and central parts) are used only for building hydraulic engineering structures of the plant [1,9].

The tectonic structure of the deposit is different in different parts. Powerful ruptures divide the deposit into three parts - southern, central and northern - within the design contour of the
open pit. As is seen from practice, the actual structure of the deposit in certain areas, especially in its southern part appears much more complicated than it was apparent based on the exploration data. In the design contours of the open pit, the reserves of magnetite quartzites of the footwall within axes $\pm 0 \div 1.8 + 120$ m of the southern end make 175398 k t. This volume of ore accounts for 98190 k $m^3$ of overburden. The average stripping ratio is 0.55 $m^3/t$; the total volume of unoxidized quartzites of the southern part of the footwall makes 223.4 M t, and that of overburden is 128.1 M $m^3$ with the average stripping ratio of 0.57 $m^3/t$.

Reserves of quartzites in the central part within axes $2.0 \div 3.4$ to the depth of 300 m make 63460 k t; in the northern part within axes $3.4 \div 4.8$ to the depth of 300 m there remains 32482 k t; in the northern part within axes $4.8 \div 7.0$ to the depth of 300 m balance reserves make 180000 k t with the average stripping ratio of 1.4 $m^3/t$. In total, within the design contours of the open pit, the remainder of the balance reserves of magnetite quartzites of the first ferruginous horizon makes 499340 k t [1, 6, 11].

Deterioration of mining conditions at mining deposits by open pit methods (increased mining depths, reduced ore deposit thickness as well as increased energy consumption) results in a decrease in working site parameters, an increase in angles of an operating pit wall and deactivation of the considerable part of the open pit due to the internal overburden dump building (figure 2). Reactivation of the open pit reserves after completion of another stage of mining leads to a surge of stripping and deterioration of engineering and economic indicators.

Figure 2. Cross section along axis 3.6: 1 – the ore deposit; 2 and 3 – the open pit contour at the end of the final mining stage and the design one respectively; 4, 5, 6, 7 – internal dumps within axes $2.6 \div 2.8$ (I stage), $3.6 \div 3.8$ (II stage), $3.0 \div 4.0$ (III stage), $2.8 \div 4.0$ (IV stage) respectively; 8 – the contour of the internal overburden dump.

In 2023, the open pit produced 6.50 M t of ore, 5.85 M $m^3$ of overburden was removed. In 2028, productivity of the southern part will make 6.2 M t of the first ferruginous horizon ore at the average stripping ratio of 1.30 $m^3/t$ (table 1).

2. Purpose

One of the solutions to this scientific and engineering problem involves combined mining of the deposit by the integrated open pit and underground methods.

The combined open pit-underground mining method enables reducing mining costs and enhancing technical and economic indicators. Implementation of scientific recommendations and technological solutions to apply the combined mining method enables a number of foreign
Table 1. Calculated rock extraction volumes at the open pit.

| Year | Ore, k t | Overburden, m³ | Stripping ratio with internal dumping, m³/t | Stripping ratio without internal dumping, m³/t |
|------|---------|----------------|-------------------------------------------|---------------------------------------------|
| 2023 | 6000    | 9600           | 1.60                                      | 1.60                                        |
| 2024 | 6500    | 9600           | 1.48                                      | 1.48                                        |
| 2025 | 7000    | 9600           | 1.37                                      | 2.04*                                       |
| 2026 | 8000    | 9600           | 1.20                                      | 2.43*                                       |
| 2027 | 9000    | 9600           | 1.07                                      | 1.32*                                       |
| 2028 | 10000   | 9600           | 0.96                                      | 0.96                                        |
| Total| 76500   | 99300          | 1.30                                      | 1.3                                         |

Note: * - considering the internal dump liquidation.

Enterprises that traditionally use the open pit method to start intensive exploitation of deposit areas previously considered unpromising.

To implement advanced mining technologies at the deposit, the practice of a number of foreign mining enterprises with a combined open pit-underground method of deposit mining is analyzed.

3. Analysis of researches and publications

The sequence of application of open pit and underground mining methods is determined considering the required productivity of an enterprise and specifics of a deposit [2,3,12–15].

The most characteristic cases of combining open pit and underground mining operations in time are as follows: combined mining of reserves by open pit and underground methods within the same deposit; final extraction of deposit reserves by the underground method after finishing open pit mining operations (OPMO); mining of reserves on promising areas of the deposit by the open pit methods and final extraction on unpromising areas by the underground methods.

Depending on the location of mine and open pit fields within the deposit, three characteristic schemes can be distinguished: with a combination of vertical operations (underground mining operations (UMO) are performed under the open pit); with a combination of horizontal operations (UMO are in the open pit wall); with a partial combination in both vertical and horizontal directions [16–19]. Kidd Creek (Canada) is an example of a gradual transition from open pit to underground mining [20–22].

The deposit of base metals has been developed since 1966 by open pit methods. The combined technology with gradual transition to underground mining exclusively has been applied since 1968 (figure 3) [20,23].

Underground mining began at the actual depth of the open pit of 150 m (the design depth -250 m), i.e. 7-10 years before completion of OPMO. The transition period from OPMO to combined open pit-underground mining lasted for about 10 years. During this period, the following tasks were performed: construction of the main and auxiliary shafts to the depth of 900 m; construction of surface and underground facilities; opening and preparation of two working levels developing; construction of the spiral ramp from the pit for delivering self-propelled equipment; construction of a complex of permanent orepasses and ventilation raises.

In the course of underground mining, the output of the open pit reduced. However, it maintained stable ore production and a constant level of workloads of the concentrating plant. The company applies powerful equipment “Ingersoll Rand”, “Mission”, “Cubex”, “Tamrock”.

Since 1996, the Australian copper-gold deposit Osborne has been mined by underground
methods in the open pit wall [24–26]. The opening of the site of underground operations is carried out through the decline adit with an entry at the level 80 m of the depleted open pit) and by vertical shafts. The Australian Northparkes deposit operated by a group of underground mines is of particular interest as it is mined by underground methods not after completion of OPMO but parallel to them.

Considerable experience in the simultaneous open pit and underground mining operations has been accumulated at the largest copper and gold deposit Grasberg (Indonesia) [27]. The mine consists of an open pit and an underground mine. The open pit provides a high production volume at a low cost. The mine develops the under-pit ore massif and several individual ore deposits near the open pit.

Vihanti, Hammaslahti, Pyhäsalmi, Haveri, Luikonlahti and Kotalahti mines (Finland) develop a number of base metal deposits by open pit, underground and combined open pit-underground methods [28].

Pyhäsalmi mine develops a deposit of copper with the copper content of 3-4 percent as well as mining lead, zinc, sulfur and rare earth elements. The deposit thickness is 20-40 m and the dip is 70-80°. The upper part of the deposit is mined by the open pit method to the depth of 120 m, the lower part - by underground mining systems with backfilling [29].

Virtasalmi deposit of base metal ores performs open pit and underground mining operations to the full depth, (figure 4) [30]. To the depth of 175 m, both open pit and underground methods were applied with transportation of extracted rock mass from the underground part to the surface along the ramp. With transition to underground mining, ventilation raises were driven from the non-mining pit wall to air underground mining operations.
Figure 4. Scheme of mining Virtasalmi base metal deposit: I – the ore body A, partially mined by the open pit; II, III – the ore bodies B and C mined by underground methods; 1 – the open pit; 2 – the open pit ramp becomes the underground one for pit trucks to go up to underground workings; 3 – the ventilation raise driven from the non-mining open pit wall berm; 4 – ventilation raises; 5 – the ore body; 6 – the mined ore.

The open pit-underground method is also used at the copper-cobalt deposit Kamoto (Congo). The steep part of the deposit directly under the open pit is mined by stoping with back filling, and the low dip one – by the room-and-pillar system. To the depth of 170 m, the deposit was mined during 15 years, and 10 years later underground mining was started.

Tyshinske base metal deposit (Kazakhstan) is represented by two steep ore bodies “Main” and “Parallel” with an 80-85° dip and thickness of 10-70 m [31, 32]. Initially, the combined method was supposed to be applied to the depth of 380 m – by the open pit method and then by the underground method abandoning a 60 m high (equal to the level high) safety pillar in the pit bottom. To maintain productivity of the mine, it was decided to work out part of the deposit by the underground method with two levels simultaneously to the concentration level. This enabled creating favorable geomechanical conditions for relieving the ore mass, decreasing costs to maintain workings, reducing ore losses and dilution [33–35].

Uchalinske deposit applies the combined method to mine gold-containing iron ores. The reserves to be mined by the underground methods make 80%, and by open pits - 20%. Since ore bodies within the same level are of different thickness, dips and useful component contents, several mining systems are applied: the heading-and-stall method with sub level breaking for thick areas (specific weight 70%); the room-and-pillar method for 5-15 m thick ore bodies (15%); the horizontal layers method for thin areas of ore bodies (15%) [36–38].

Goroblagodatske iron ore deposit in Sverdlovsk region (Russia) is the largest [39, 40]. Ore bodies are represented by a series of sheet, tectonic, disturbed 200-1800 m long bodies with 30-75° dips and thickness of 2 to 84 m. The ores are exposed. The deposit is mined by open pit and underground methods. The depth of mining is 420 m and 200 m. The underground part of the deposit is mined by induced block caving with long hole breaking and back filling of the worked out area with self-caved rocks of the hanging wall. The height of the level varies from
60 m to 80 m. Average losses and dilution make 5-8%, up to 15% respectively [41–43].

The analysis performed enables ascertaining that in the world practice there is a steady trend of additional underground mining of deposit areas with unfavorable conditions for open pit mining operations.

The combined mining method enables reducing the level of environmental damage caused by open pit mining and increasing efficiency of underground operations [44–46]. Almost all considered enterprises that started mining reserves by open pit methods, implement gradual transition from open pit to underground mining, creating integrated geotechnological systems “open pit-underground mine” at the deposits.

All technological solutions at underground mines that are being built or operating focus on using highly efficient options of mining systems and types of self-propelled equipment. A characteristic feature of combined mining is the use of the general transport system “open pit-mine”. In some cases, deposit areas are opened for underground mining operations by vertical shafts equipped with high-speed automated hoisting units.

Complexes of inclined and horizontal workings – ad its and spiral ramps – ensure efficient operation of self-propelled equipment and increase productivity of the mining enterprise. Experience shows that in most cases it is most efficient from the engineering and organizational points of view to drive horizontal and inclined transport transportation workings from the open pit side [47–49].

4. Methods

Determination of parameters of mining operations when applying the combined open pit-underground mining methods possesses certain specific features. They include the final depth of the pit (the open tier – OT), the boundary of transition from open pit to underground operations (the open pit-underground tier – OUT), the beginning of underground operations (the underground tier – UT) [50–52].

When determining the parameters of OT and OUT, the methods used for OPMO are applied [2–4] and technological features of determining parameters of mining operations in combined mining are also considered [53–55].

In combined mining, due to determined technological features [1,6,7], such concepts as “final depth of the open pit” and “boundary of transition from open pit to underground operations” are distinguished. Obviously, the moment of transition to underground operations occurs long before reaching the maximum depth of the open pit and lasts long (up to 10–15 years). In addition, with a one-time assessment of the sequence of mining the reserves of the entire deposit, all the technological features of the design solutions should be considered [56–58].

The beginning of the transition [1] corresponds to the current depth of the pit which is determined by duration of complete mining of the deposit in a given range of depths and duration of construction of the underground mine to work with the reserves below the open pit bottom

\[ H_{kt} = H_k + (M - B_d) \times 0.5 \times \tan \gamma - T \times h, \]  

where \( H_k \) is the increase of the pit depth that depends on the slope angle of the operating wall, m; \( M \) is the thickness of the deposit, m; \( B_d \) is the pit bottom width, m; \( T \) is duration of underground mine construction, years; \( h \) is the rate of pit deepening, m/year.

The value of deepening open-pit ore mining operations without moving the pit walls apart is determined by thickness of deposits, slope dips and width of the pit bottom according to the formula

\[ H_k = \frac{M - B_d}{\text{ctg} \beta - \text{ctg} \beta_1}, \]
where $\beta_v$, $\beta_1$ are the slope dips of the pit walls considering strength degradation of rocks in the transition zone of non-mining and operating walls respectively, degrees.

According to Starikov N and Novozhylov M, it is more accurate and scientifically justified to determine the value $H_k$ considering possible losses and discrepancies between the calculated and actual losses when extracting ore pillars near the wall, and the cost of mining production in this area [59–61]

$$H_k = \frac{K \times (M - B_d)}{(1 - K)(ctg\beta_v - ctg\beta_1)},$$

(3)

where $K$ is the coefficient characterizing the maximum permissible relative value of the ore volume remained in the wall pillars (it varies from 0.1 to 0.5). In general, the value $H_k$ is the height of the transition zone, since it is in this zone that transition to parallel (simultaneous) production of open pit and underground mining operations and a single worked-out area can be created. The height of the transition zone is determined by the formula

$$H_k = \frac{\sqrt{M(K_p - K_{op})^2 + H_k(K_p - K_{op})(M - B_d)(2 - K_{op} - K_o)(ctg\beta_v - ctg\beta_1)}}{(1 - K_{bz})(ctg\beta_v - ctg\beta_1)},$$

(4)

where $K_o$, $K_{op}$, $K_p$, $K_z$ are ore extraction ratios at open pit, open pit-underground, underground mining operations and at pillar extraction respectively.

Thus, the boundary of transition from open pit to underground mining operations is the boundary parameter of the combined (open pit-underground) mining of steep deposits determined by the total final depth of the open pit and the height of the transition zone that should be calculated considering technological features of the deposit.

When determining the boundary of transition for operating open pits, a preliminary assessment of the possibility and efficiency of transition to the combined method is first performed according to the criterion of the minimum estimated operating costs for mining the entire deposit. Then the obtained results are corrected and used to finally justify economic efficiency of transition (boundaries and terms) from open pit to underground mining. This task is solved at the stage of engineering design development considering additional factors: geological, hydrogeological, economic, technological, engineering, climatic, ecological, social.

As is seen from the design practice, the methods of large-scale assessment of the possibility and efficiency of transition to underground mining prove to be expedient. Analysis and consideration of indicators of the current open pit performance (primarily economic, the cost of production being the main of them) are a prerequisite for this assessment [62–64].

The cost of production both at open pit and underground mining methods is the most generalized, concentrated indicator of efficiency of mining enterprise performance. Despite the available reserves of reducing the cost of mining, it tends to grow as the depth of mining increases throughout the entire period of deposit operation.

The main reason for growth of the mining cost is a constant increase in the mining depth which leads to an increase in the volume of overburden rocks, especially hard rocks, an increase in the transportation distance, an iron content decrease in most cases. Correlation analysis of actual indicators of Kryvbas open pits demonstrates that the increase of the depth by 10 m results in the production cost increase by 11–12% and the cost of stripping – by 13–16% [65,66].

The final depth of the open pit is determined by minimizing the cost of mining to the depth $H$ considering transition from open pit to underground mining operations and dynamics of the mining production cost

$$\sum K_v = C_r V_r + C_o V_o + C_{op} V_{op} + C_p V_p,$$

(5)
where $K_v$ is the cost of mining, USD; $C_r$, $C_o$ are the cost of 1 m$^3$ stripping and mining by open pit methods respectively, USD/m$^3$; $C_{op}$, $C_p$ are the cost of open pit-underground and underground mining, USD/t; $V_r$ is the volume of stripping, m$^3$; $V_o$ is the volume of ore mining, m$^3$; $V_{op}$, $V_p$ are volumes of ore production by open pit-underground and underground methods respectively, m$^3$.

In today’s market economy, with self-financing of mining and capital works, performance efficiency of mining enterprises applying underground methods and carrying out reconstruction in order to maintain design production volumes should be provided by the condition

$$T_1 = T_2,$$  \hspace{1cm} (6)

where $T_1$ is the time of mining the upper level, months; $T_2$ is the time of opening and construction of the lower level, months.

During construction of an underground mine from the open pit side, the time spent on preparation of the UMO start site should not exceed duration of additional mining of the open pit (a section of the open pit) to the maximum depth. This will allow maintaining production volumes and achieving the maximum economic effect.

In turn, the time spent on final extraction of reserves by open pit methods in the case of steep deposits can be presented as the function of the difference between the actual and final depths of the open pit and the rate of OPMO reduction.

Thus, the maximum profit received from mining and sales of useful minerals is due to timely provision of UMO area construction that excludes both early completion of open pit operations not related to the beginning of mining on the built level, and delay in construction of the underground complex

$$P = f(T_{lk}) \rightarrow \max \hspace{1cm} \text{at} \hspace{1cm} T_{actual} = T_{optimal}. \hspace{1cm} (7)$$

To ensure the optimal level construction time that corresponds to the rate of reduction of mining operations in the open pit, it is necessary to determine rates of constructing the underground complex.

5. Results

In underground mining in the zone of OPMO influence, choosing a scheme for opening and preparing the ore deposit considering mining conditions in the open pit is the most important factor. Main parameters of the opening scheme include the size of the mine field, location of main opening operations and ventilation workings, the scheme of haulage (transportation) levels [1].

Applying combined open pit-underground mining, the necessity to select opening schemes both for open pit and mine fields and the technological combination of open pit-underground mining processes often depend on efforts to make the most of the specific features of the deposit mining in order to increase its mining efficiency.

In underground and combined open pit-underground mining at Hannivske deposit beyond the contours of the OPMO stage, several technological schemes can be used within the design contours of the open pit. They differ in mining methods, loading, transporting the ore mass onto the surface, (figure 5).

Thus, the scheme (see figure 5 (a)), a provides for application of a system with bulk ore and country rocks caving, loading ore from the block into underground minecars by vibrofeeders and ore hoisting in a vertical shaft. The scheme (see figure 5 (b)) is distinguished by the method of transporting the rock mass from the stope to the shaft (underground trucks).

Traditional technological solutions (figure 5 (a) and figure 5 (b)) require building permanent ore hoisters and auxiliary ventilation shafts with appropriate surface complexes, transport and other communications, which is economically and organizationally impractical.
Figure 5. Schemes of opening and transporting the mined rock mass in combined open pit-underground mining. 1 – the vertical shaft with the skip winder; 2 – the crusher; 3 – haulage workings; 4 – the minecar; 5 – the vibrofeeder; 6 – the ore bell (drawpoint); 7 – the ventilation-auxiliary shaft; 8 – the broken ore; 9 – the permanent internal dump; 10 – the underground mine truck; 11 – the tippler; 12 – ore reloading yard in the open pit; 13 – the pit excavator; 14 – the pit truck; 15 – the protecting pillar; 16 – the underground hydraulic excavator; 17 – ventilation holes (trunks); 18 – the load-haul vehicle.

The most successful solution to the problem of combined open pit-underground mining of Hanniiske deposit involves low-cost technological schemes. Their options, most suitable for these conditions, are presented (figure 5 (c) and figure 5 (d) and figure 5 (e)).

Scheme c provides for application of a system with bulk ore and country rocks caving, loading the ore from the block into underground minecars by vibrofeeders and transporting the ore in the adit on the open pit wall.

Scheme d provides for application of a system with bulk ore and country rocks caving and ore drawing under the protective pillar. The ore from the block is loaded into underground trucks by underground excavators and transported in the adit on the open pit wall.

Scheme e provides for application of a system with bulk ore and country rocks caving, loading the ore from the block into underground minecars by loaders and transporting the ore in the adit on the open pit wall. These schemes involve various combinations of the following elements...
of the technology:
- at the stage of mining reserves – use of the room system with abandoned pillars within the mining blocks; use of induced block caving with a set of measures to prevent dilution of the broken ore with overlying rocks under the internal dump;
- at the stage of ore transportation and loading – use of high-performance vibrodrawing options (with twin vibrofeeders), implementation of excavator loading, use of high-performance load-haul vehicles;
- at the stage of ore transporting and hoisting onto the surface – use of self-propelled equipment with ore hoisting to reloading yards in the open pit.

At underground mines, when using high-performance self-propelled equipment, selection of a rational scheme of opening and preparation gains crucial significance for achieving the best results in terms of capital and operating costs reduction.

Application of self-propelled machines leads to a change in traditional opening schemes and conditions important features of deposit preparation. At the current level of mechanization, engineering indicators of underground production will be almost similar to those at OPMO. It is advisable to start mining from the southern flank of the site northwards, the transport adit is driven from the level -120 m, and the ventilation adit – from the level -20 m in the hanging wall of the deposit. Reserves of the level -165±0 m should be divided into two levels. The height of the first level is 105 m at the mark -105±0 m, and of the second one is 60 m, in the mark -165±105 m.

In this regard, opening, preparation and mining of levels are performed in two stages, (figure 6): the first stage – reserves are mined at the level -105±0 m; the second stage – reserves are mined at the level -165±105 m.

Figure 6. Deposit opening (option I): 1 – the ventilation adit; 2 – the drilling adit for mining the upper level; 3 – the loading and transportation adit for mining the reserves of the upper level and the drilling adit for mining the lower level; 4 – the ramp; 5 – the ventilation and manway raise; 6 – the loading and transportation adit for mining the lower level reserves.

Main opening workings in underground mining within the first stage are the transportation adit from the level -120 m to the level -165 m, the haulage adit from the northern end of the southern section of the open pit on the level -120 m to the level -105 m directly beyond the deposit. The drilling adit on the level -60 m, and the ventilation adit on the level -30 m, are located on the hanging wall of the deposit, (figure 7).

When mining at the second stage, the haulage adit of the -105 m level will become a drilling one, and the haulage and transportation adits will be located on the level -165 m. The transportation and ventilation adits are driven immediately from the northern end of the southern section to the southern end of the northern section. The length of the adits is 1500 m and 1150 m respectively.

Loaded and empty vehicles travel in the adit using a centralized signalling and communication system. Preparation of the mine field is of the ort kind at dead ends. Access orts are 40–60 m long (depending on the ore body thickness) and equipped with loading points. The length of the haulage and drilling adits is determined by mining and geological conditions.
Figure 7. Deposit opening (option II): 1 – the ventilation adit; 2 – the drilling adit for mining the upper level; 3 – the loading and transport adit; 4 – the ramp; 5 – the ventilation and manway raise; 6 – the loading adit for mining the upper level reserves and the drilling adit for mining the lower level.

The total length of the haulage adit is 1500 m, and that of the drilling one is approximately 1000 m. Development and ventilation workings on areas of the second and subsequent stages of underground mining are driven as the reserves of previous areas are worked out. The mining blocks are prepared by 33 two-way access orts of 60 m each. Their total length makes 1980 m.

For effective ventilation of stoping in the hanging wall of the ore body, one ventilation-manway raise from the level -105 m to the level -30 m for every three blocks and a 1000 m long entry-collector on the level -105 m are built. The total number of raises is 16; their total length is 1200 m. Mining Hannivske deposit by the open pit-underground method will increase intensity of mining operations, efficiency of the enterprise and, accordingly, reduce the need for areas for external dumps. Therefore, the production capacity of the underground mine should be determined as the most possible according to annual production of minerals of the required quality.

When calculating the annual production value, operation indicators of the deposit are accepted for conditions of the most complete use of means of production, the rational mode of operation, application of the efficient technology and organization of activities of the mining enterprise which considers best practices and ensures compliance with safety requirements and technical operation rules.

Underground mining of the central part of Hannivske deposit is designed within axes 2.4±3.4 ±0 m, with the level height of 165 m. According to calculations, the estimated economically feasible annual productivity of the underground mine is 3.18 M t/year, and by mining capabilities – 3.17 M t/year.

According to [6], optimization of the design productivity of the mine should be carried out on a scale of the mineral and raw material region where there is interrelation between consumption and production of this type of minerals. In the current economic conditions, considering possible iron ore product sales in the national and foreign markets, to compensate for the productivity loss due to the reduction in open pit mining volumes in the central part of the open pit, it is advisable to accept an annual productivity of 3 M t/year.

In this case, the service life of the underground mine \( t_p \), considering final mining of the central part of the open pit within axes of 2.4±3.4, level -165±0 m and the average loss factor \( k_n = 0.85 \), will make 18 years. The obtained value \( t_p \) meets the requirements [16, 17] for enterprises with a mineral concentration complex.

Technical solutions for the underground mine should be assessed on the basis of two main principles: the underground mine, despite a more complex technology and a relatively small share of the total production (15–20%), should provide an increase in efficiency of the main, open pit method; the technology of underground mining and the technical level of equipment should be as close as possible to those during open pit mining operations.

Broken rock mass is drawn and loaded using powerful loading and transporting equipment.
in the following combinations: hydraulic excavator – truck; load-haul units – truck; twin vibrofeeders – truck.

Based on the calculations performed, to ensure annual production of 3.0 M t/year, it is advisable to apply the following combination of transport equipment: load-haul units – truck. At the same time, six MT5010 trucks and three ST1810 load-haul units should operate simultaneously. For the specified mining and geological conditions, it is advisable to use an induced block ore caving system or room mining. It should be noted that when applying a room mining system with abandoned pillars, ore losses increase, and further disposal in the internal dump is not allowed. Thus, we finally adopt the system of induced block ore caving with breaking ore by parallel contiguous rings of longholes onto the vertical compensatory room.

The first 105 m high level is opened by horizontal adits driven from the open pit wall on the levels: -120 m (transportation), -60 m (drilling) and -30 m (ventilation). This option of the mining system is used, as a rule, for mining thick steep deposits.

In order to apply technological solutions that meet the minimum-operation principles, it is advisable to draw ore from a panel through loading points. The panel and blocks are located with their long sides across the strike of the ore deposit, their length depends on thickness of the ore body (120 m), and the width of the panel is accepted 30 m. Ore reserves in the panel make $V_k = 1.28$ M t and the term of their mining is $T_0 = 0.43$ year.

To ensure the design annual productivity of 3.0 M t, three panels should be mined at a time. If the panel width is accepted to equal 30 m, the mining block width will make 90 m. Annual productivity is ensured subject to simultaneous operation of three blocks: 1 – preparatory, 1 – development and 1 – mine.

In conditions of intensive operation of self-propelled equipment, effective ventilation of stoping is provided by a forced ventilation system. It includes horizontal ventilation and manway workings on the level -30 m, ventilation raises from the level -165 m to the level -120 m and from the level -120 m to the level -30 m and a ventilation adit on the level -30 m.

Mining operations are aired according to the suction scheme. Fresh air is supplied through the adit entry, dilute exhaust gases of self-propelled equipment motors to the permissible sanitary standards and flow about workings.

According to the calculations, the period of building a start-up complex with the average per shift productivity of drifting faces of 40 m$^3$/shift and with the three-shift mode will make $T \approx 18$ months. It should be noted that mining is carried out whenever required. At that, the total mining productivity can be increased by combining technological operations in several faces.

The total costs of mining operations required for commissioning the start-up complex is 2.5 M USD, the cost of mine equipment acquisition at the time of building the underground mine is 4.9 M USD. Considering the cost of equipment necessary for the construction, capital expenditures for the start-up complex will amount to 7.4 M USD. The total capital expenditures, considering the cost of additional equipment required to start stoping make 6.7 M USD, for mining and capital works – 2.3 M USD, and the total amount makes 9.0 M USD.

When mining a 90 m long and 105 m high area with the thickness of 120 m, the reserves to be mined will make 3.84 M t. Specific capital expenditures per tonne of ore reserves of the central section of the pit will be 0.26 USD/t.

The data characterizing efficiency of the underground mining enterprises of Kryvbas that apply elements of minimum-operation technology in their production cycle is used to determine the cost of extraction of 1 tonne of ore. In particular, a typical example of the above is Ordzhonikidze underground mine as part of the Central Mining and Processing Plant (Kryvyi Rih, Ukraine).

Similarly, on the UMO area of the open pit, the expected underground mine cost of ore production will make 13.69 USD/t, and the total cost will be 15.84 USD/t (table 2).

The consolidated technical and economic indicators of the combined (open pit-underground)
Table 2. Expected production costs of 1 tonne of ore during underground mining on the area of stage I of UMO.

| Indicators                                  | Costs, USD/t | Specific costs, % |
|---------------------------------------------|--------------|------------------|
| Raw materials and basic materials           | 3.33         | 21.02            |
| Remuneration of labor                       | 2.16         | 13.61            |
| Social Security deductions                  | 0.78         | 4.93             |
| Auxiliary materials                         | 0.46         | 2.85             |
| Energy costs                                | 3.4          | 21.4             |
| Fixed assets (deductions)                   | 2.18         | 13.75            |
| Service sector                              | 0.3          | 1.95             |
| Depreciation of fixed assets                | 0.25         | 1.57             |
| Equipment maintenance repair costs          | 0.16         | 1.04             |
| Other                                       | 0.68         | 4.26             |
| Underground mine cost                       | 13.69        | 86.38            |
| General operating expenses                  | 1.52         | 9.6              |
| Non-production costs                        | 0.64         | 4.02             |
| Total cost                                  | 15.84        | 100              |

mining of the balance reserves of Hannisvke deposit are presented in table 3.

Table 3. Indicators by options under comparison.

| Indicators                                                                 | Option/t | Option |
|---------------------------------------------------------------------------|----------|--------|
| Annual production volume, including by areas, M t.:                       | 10.0     | 10.0   |
| -OPMO                                                                     | 10.0     |        |
| -UMO                                                                      | 3.0      |        |
| Cost of ore mining incl. transportation of overburden (excl. rocks removal from the internal dump), USD/t | 9.93*    | 11.70**|
| Costs for liquidation of the internal dump (per 1 t of mined ore), USD/t  | 5.14*    |        |
| Specific capital investments, USD/t                                      | 0.26     |
| Costs of mining 1 t of ore, USD/t                                        | 15.07    | 11.96  |

Note: * - actual technical and economic indicators from open pit works for 2019; ** - weighted average indicator for OPMO + UMO.

Comparison of the obtained indicators of open pit-underground mining with those of open pit mining confirms the viability of the open pit transition to application of the combined method of mining reserves under the internal overburden dump.

In this case, the central part of the open pit can be used to form a permanent internal dump with a capacity of over 300 M m³. The total duration of mining and capital works, considering the previous period, is 2 years.

The first year accounts for 7.35 M USD for mining operations and acquisition of equipment...
necessary to start construction. Expenditures of the second year consist of costs of equipment necessary to start stoping and mining operations and amount to 9.05 M USD.

6. Conclusions
The analysis conducted enables ascertaining that the global practice of sustainable development demonstrates a trend to apply underground methods to additionally mine deposit areas with unfavorable conditions for open mining operations. Mining deposit by the combined method enables reducing environmental damages caused by open pit mining and increasing efficiency of underground operations.

Almost all considered enterprises that started mining reserves by the open pit method are implementing gradual transition from open pit to underground mining creating integrated geotechnological systems “open pit-underground mine” at the deposits. All technological solutions at underground mines that are being built or operating focus on using highly efficient options of mining systems and types of self-propelled drilling, haul and transportation equipment. In some cases, deposit areas are opened for underground mining operations by vertical shafts equipped with high-speed automated hoisting units.

The suggested complexes of inclined and horizontal workings ensure efficient operation of self-propelled equipment and increase productivity of the mining enterprise to 3 M t/year. Based on the calculations performed, it is advisable to apply the following combination of transport equipment: six MT5010 underground trucks and three ST1810 load-haul units.

When applying the combined method to mine reserves under the bottom of Hannivskyi open pit by underground methods, the cost of production will decrease by 3.11 USD/t, of which 0.26 USD/t are specific capital investments for underground mining. The total amount of capital expenditures will amount to 16.4 M USD.

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