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PRINCIPLES OF ROCK PRESSURE ENERGY USAGE DURING UNDERGROUND MINING OF DEPOSITS

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ПРИНЦИПИ ВИКОРИСТАННЯ ЕНЕРГІЇ ГІРСЬКОГО ТИСКУ ПРИ ПІДЗЕМНІЙ РОЗРОБЦІ РОДОВИЩ

Purpose. To substantiate principles of rock pressure usage during underground mining of deposits.

Methodology. Zonal structuring indices of massif around mine workings were established with help of industrial, laboratory and theoretical research of stress-strain state of rock massif. Research on entropy influence on energy exchange and deformations developments in undisturbed rock massif is conducted by means of the entropy method. Research on preventive capsule formation processes around mine workings and forms of energy transition into work of rock deformation is executed with help of the energy method. Development of geo-energy approaches for the choice of development workings pathways and calculation of their bolting parameters as well as substantiation of parameters of conducting stoping operations in energy zones of preventive capsules is executed according to the estimation of geo-energy technology effectiveness and realization of industrial implementation during underground mining of deposits.

Findings. Physical essence of zonal capsulation phenomenon of mine workings is revealed. Geo-energy principles of rock pressure energy usage are substantaited. Resource-saving technologies of mining of mineral depositis are created and implemented into production.

Originality. The paper deals with systematization of the picture of phenomena, capsulation processes and regularities by massif of mine workings with determination of shape, sizes, quantity of energy zones, sinusoidal-damping stresses and ring modules of deformation by means of complex account of geo-energy factors that allow using energy of rock pressure in underground mining technologies systematically.

Practical value. The energy prediction theory of zonal capsulation parameters research of mine workings is developed which allows studying shapes, sizes, quantity and conditions of formation of energy zones and borders of possible destruction of the massif. Power dependences are established as to changing the sizes of adjacent power zones whose ratio is a constant from the sizes and shape, depth of laying and physical properties of massif containing mine working. The thermodynamic theory of massif that is not disturbed by workings is improved by means of considering the processes of geo-energy streams redistribution and entropy exchanging with allocation into undisturbed massif in a separate entropy method of research. Further development of the sinusoidal-fading dependence of auto-wave fluctuations of stresses in massif that broken by mine workings from gradients of density, temperature, gas-and water saturations of rocks is given.

Keywords: *rock pressure energy, stress-strain state of rocks, synergetic research methods, preventive capsule of mine working, geo-energy technologies of mining*

Introduction. For the last decades, mining depth of deposits has exceeded a mark of 1500 m worldwide that is followed by considerable deterioration in geodynamic conditions of mining. Elastic potential energy appears not only in the form of peelings and cleavages, but also in the form of rock bursts and earthquakes of various amplitude that began to occur within the Ukrainian crystalline shield. The analysis of production information on ore deposits of Ukraine has shown that in elastic strong rocks (granites, amfibolita, quartzites) at depths over 1200 m (the Kryvorizskyi basin) zones of inhomogeneously stressed rocks which are followed by formation of ring-shaped areas of the excessive crack content are intensively formed. In elastic-plastic rocks (martitovy, getitovy ores) at depths over 900 m (the Kryvorizskyi basin) ring-shaped zones of lowered stresses are divided by intensively contorted ores. In plastic rocks (manganese ores, clays, clay-bearing soils) at depths up to 350 m (Nikopol-Marganetskyi basin) processes of zonal convergence and divergence are actively developed. These processes lead to destruction of mine workings and loss of mineral reserves, damage of objects on the surface and in the subsoil, and unfortunately, to traumatizing and death of people [1].

Outstanding issue. Both Ukrainian scientists and their colleagues worldwide have been actively involved in development of theories of rock pressure around underground mine workings, among them were M. M. Protodyakonov (1908), A. N. Dinnyk (1925), O. V. Savostyanov (1974), V. F. Lavrinenko (1975); in Russia – F. Levinson-Lesing and A. Zaitsev (1915), J. Spelding (1937), R. Fenner (1938) and V. D. Slesarev (1948), R. Kvapil (1958); in Germany – P. Schulz (1867), V. Ritter (1879), F. Engesser (1882), V. Trompeter (1899), G. Mantsel (1894); in Austria – O. Kommerel (1912), A. Leon (1908), in France – J. Talobr (1878), N. Feyol (1885), Switzerland – A. Game (1878); in England – N. Hast (1967). Overwhelming majority of researchers considered changes of stresses of the massif according to the extent of influence on parameters of mine working bolting and development systems. The analysis of scientific results has shown that the zonal condition of the massif was revealed by V. Trompeter (1899) and further researchers described only separate processes of this phenomenon. It has resulted in the fact that many theories are not consistent with each other, and some of them contradict laws of physics. Results of the conducted research have not allowed defining quantity, shape and sizes of zones of unloading concentration of stresses and areas of deformation of the massif. None of the theories, except thermodynamic one (V. F. Lavrinenko, 1975), managed to describe a condition of undisturbed and broken massif by mine workings, nor did they develop a certain approach to its description. It gives evidence of necessity to develop modern theoretical ideas of rock pressure for the purpose of disclosure of physical essence of the phenomenon which is describing a zonal condition of the massif that would allow solving the problem of rock pressure energy usage while bolting and supporting mine workings [2].

Analysis of the recent research. The analysis of Ukrainian developments regarding the ways of mine workings supporting shows that modern scientific and, respectively, production representations, on which the majority of the Ukrainian technologies of mine workings bolting and supporting is based, are founded on two basic principles. 1. Support counteraction to destruction of bearing massif due to change of their types, parameters of installation and service conditions for achievement of the maximum repulse of bolting system. It involves scientific developments of authors who make the most part of the total number of researchers: A. N. Zorin (2001), A. F. Bulat [3], V. V. Vinogradov (2002), T. A. Palamarchuk [4], A. I. Zilberman (1978), V. I. Bondarenko [5], P. I. Ponomarenko (1991), G. A. Symanovych [5], L. N. Shirin (1994), V. I. Buzylo [6], Yu. M. Khalymendyk [7], I. A. Kovalevska [8], V. Ya. Kirichenko [9], A. H. Katkov (1984), I. S. Zitser (1986), A. P. Grigoriev (1992), V. I. Nikonets (2003) and many others. 2. Equilibration of stability of the massif with parameters of mine workings by changing their sizes and shape for achievement of the maximum stability of contours of exposures. These research studies make a smaller part of authors from the total number: E. I. Logachev (2006), V. O. Kalinichenko [10], V. P. Voloshchenko (2000), V. V. Carikovskii [11], Yu. I. Koshik (1992), V. I. Golik (1998), V. I. Liashenko [12]. If the principle of counteraction is generally used for development mine working supporting, then the principle of an equilibration is for increasing stability of stoping chambers. Both principles do not allow using rock pressure energy, they only provide decreasing costs of bolting and supporting of mine workings due to optimization of technological parameters.

Unsolved aspects of the problem. The majority of scientific developments have applied format being based on the principle of counteraction to the increasing rock pressure energy and setting a goal only to minimize costs of production. Such approach did not allow establishing physical essence of the phenomenon of zonal disintegration of rocks, which is shown around one and all underground mine workings, that has suspended development of fundamental theories about rock pressure a little. The applied approach became a certain obstruction in a way of developing new hypotheses, theories or methods which would describe or model zonal structuring of the massif around mine workings. The conducted analysis has allowed revealing two new principles applying which it is possible to use rock pressure energy. These are the principle of assistance that was underlain by Yu. P. Kaplenko (2004) and B. N. Andreev [13] in technology of layers of ore breaking which are situated in areas of intensive deformation or zones of stresses unloading, and also the principle of elimination used by V. S. Nigmatullin (1979) as finding of rational places of laying of development mine workings towards stoping chambers.

Objective of the article. The analysis of the processes and principles of management of natural and technological factors has opened a possibility of rock pressure energy usage in technologies of mining of deposits. Thus, it is possible to set the objective of the research to prove the principles of rock pressure energy usage during underground mining of deposits.

To achieve the stated purpose, improvement of classification of research methods for stress-strain state condition of rocks by means of development was made, and introduction of synergetic group of the methods including entropy, thermodynamic and energy approaches allowed investigating processes of energy exchanging in rock massif and natural transformations of some types of energy into others. The existing possibilities of an entropy method as part of the thermodynamic theory, consisted in opportunities of the description of thermodynamic balance in rocks and reversible deformations in undisturbed massif of rocks (V. F. Lavrinenko), and also exchange of entropy and redistributions of energy flows in rock massif (O. Ye. Khomenko). The thermodynamic method has allowed defining a shape and sizes of unloading zones of stresses around mine workings, the potential and actual stresses, areas of massif destruction in unloading zones (V. F. Lavrinenko). The power method has allowed defining the form and the sizes of zones of thermodynamic balance of energy, a condition of transition of zones to a condition of energy disbalance, quantity of energy zones in the safety capsule and intensity of minor factors of massif actual stress around mine workings (Fig. 1).

Geo-energy factors, parameters of stress-strain state of the massif of rocks which include pressure, stress, density, temperature, gas-and water content had impact on formation of safety capsule around underground mine working. Research methods of transitional conditions of rocks at simultaneous changing of gradients of several geo-energyr factors were used for their stydying (stress and temperature, pressure and density, gas-and water content).

Energy flows (flows of energy) are the directions of changing specific energy consumptions in the rock massif containing underground mine working. Zonal capsulation of mine working is a process of formation of interconnected energy zones in the surrounding massif with changing gradients of geo-energy factors. The safety capsule of underground mine working is an ellipsoidal part of the massif consisting of several energy zones characterized by existence of extrema of changing gradients of geo-energy factors. Energy zones represent ring-shaped ellipsoidal subareas of the safety capsule which are limited to the surface of the massif with natural values of gradients of geo-energy factors (γH). Depending on a condition of rocks in the energy zone and on its situation in the capsule, zones of thermodynamic balance and disbalance of energy are allocated. The zone of thermodynamic balance of energy is an energy zone in which the operating total stress does not exceed strength

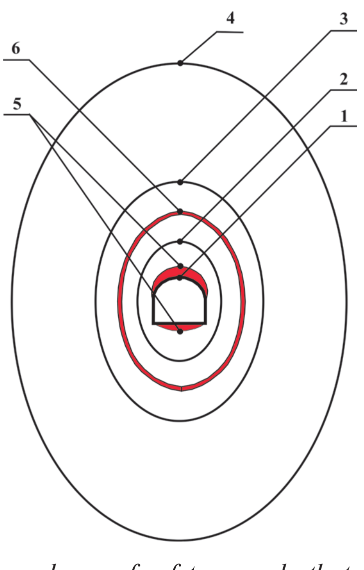


Fig. 1. The scheme of safety capsule that was created around underground mine working:

1 – contour of development mine working; 2 – zone of thermodynamic energy disbalance No. 1 (unloading, near-the-contour zone); 3 – zone of thermodynamic energy disbalance No. 2; 4 – zone of thermodynamic energy balance; 5 – areas of massif deformation on mine working contour; 6 – ring area of massif deformation

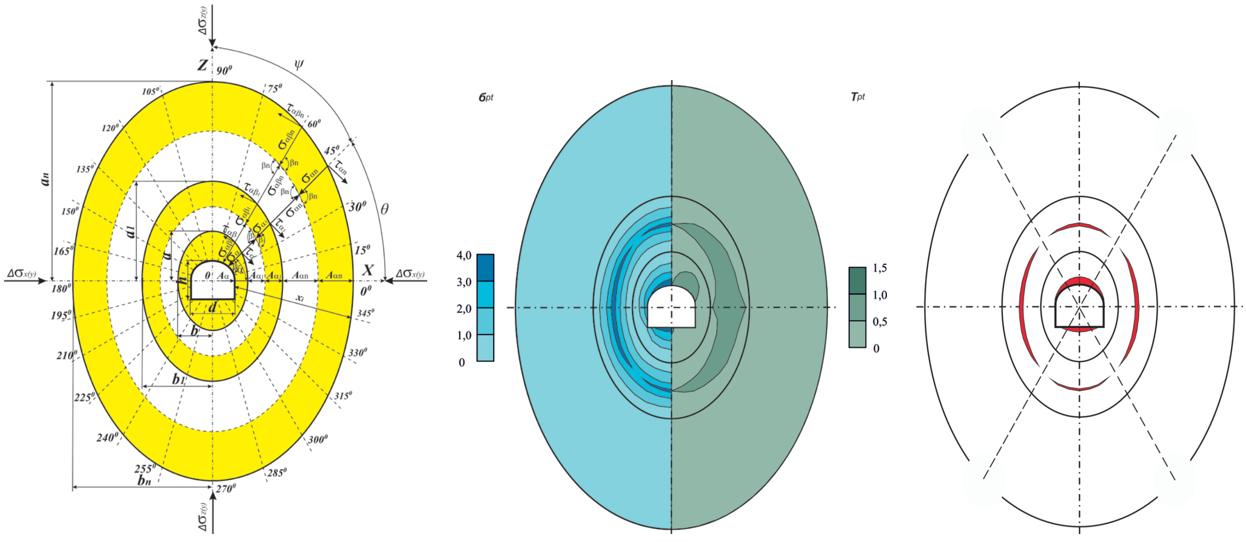
of rocks on compression or stretching. The zone of a thermodynamic disbalance of energy is an energy zone in which the operating mechanical stress exceeds resistence of rocks to compression or stretching, forming areas of massif deformation.

Presentation of the main research. It is established that distribution of entropy in the undisturbed massif of rocks of the Ukrainian crystalline shield occurs in mutually perpendicular directions which coincide with the vertical and horizontal directions of redistribution of geo-energy factors by means of an entropy method. So, with a vertical pressure of 50 MPa at a depth of 1500 m in the massif only a part of potential energy whose volume for horizontal stresses is equal to 50 %, and for vertical up to 45 % is redistributed. The increase in vertical pressure up to 91 MPa at depths up to 3000 m leads to redistribution of potential energy in the massif of rocks of the Kryvorizskyi basin whose volume for horizontal stresses is equal to as little as 95 %, and for vertical up to 57 %. Definition of a shape and sizes of energy zones in the safety capsule was made regarding the relation of vertical $\Delta\sigma_{z(y)}$ and horizontal $\Delta\sigma_{x(y)}$ of potential stresses which define a coefficient of a zones shapes λ which decreases from 1 to 0 during decrease in rock strength from 200 to 40 MPa and increase in depth of mine working up to 3000 m according to the system of exponential dependences, at that

$$\lambda = \Delta\sigma_{z(y)}/\Delta\sigma_{x(y)}. \quad (1)$$

The massif of rocks which forms the safety capsule around development mine working represents an elliptic cylinder, and for stoping chamber it is a rotation ellipsoid. The sizes of vertical *a* and horizontal *b, c* semi-axis of energy zones which are formed in the massif containing mine working are defined with the usage of coefficient λ. Accuracy of the executed calculations is confirmed by comparison of the obtained data method of unloading and calculated values of elastic deformations of rocks at depths up to 1200 m in mine fields of "Zhovtneva" and "Ternivska" mines of "Kryvorozskyi Iron Ore plant" PJSC – 3–5 %. The calculated and experimentally established density of rocks under pressure to 1.5×10^3 MPa differ among themselves on average for 1.32 %, and density of minerals – for 2.15 %. Values of relative volume deformation of minerals with a pressure to 4×10^3 MPa have been compared with experimental data for conditions of high pressure, and the divergence has not exceeded 7.9–10.6 %, and the measured and calculated velocities of distribution of longitudinal elastic waves in rock massif which is not broken by mining operations differed for 6–8 %.

Theoretical research. Parameters of capsules formation were investigated using an energy method by means of "convergence" and "divergence" categories which are phases of centripetal self-organization of open systems according to the basic principles of synergetics and thermodynamics relating to the elastoplastic environment. In the course of convergence, the massif containing underground mine working is divided into the integration subbands (allocated with a background – Fig. 2, *a*), but during divergence – disintegration sub-



a b c

Fig. 2. The scheme to calculation of parameters of safety capsule created around development mine working (a) fields of radial σ_{pt} and tangential σ_{pt} of total stresses in the massif of zones of thermodynamic energy balance, MPa (b) [14], formation of areas of massif deformation in zones of a thermodynamic energy disbalance (c, highlighted background) [14]

bands. Underground mine working is an epicenter of energy balance violation in the massif of rocks and by means of convergence and divergence the massif counteracts formation of any emptiness in it and tend to recovery of its integrity by its capsulation of development mine workings by system of ring energy zones [6].

Sizes of vertical and horizontal semi-axis of energy zones are, m

$$a_n = 0.5((n-1)b\lambda^{-1} + (n-1)a);$$
$$b_{n-1} = (n-1)a\lambda; \quad c_n = b_{n-1}, \qquad (2)$$

where *a*, *b* and *c*, *d* are widths and *h* is height of development mine working, m.

The initial potential stresses of compression from borders of near-the-contour and the subsequent energy zones to a massif exposure surface act with mine working along the settlement platforms which making with stresses of $\Delta\sigma_{x(y)}$ angles $0 < \alpha < 360°$.

Radial σ_r and tangential τ_r stresses of the undisturbed massif on all settlement platforms with directions of stresses $\Delta\sigma_{z(y)}$ angles of α, MPa as a result of release of internal energy of the massif are

$$\sigma_{\alpha n} = \Delta\sigma_{X(Y)} \cos\alpha^2 + \Delta\sigma_{Z(Y)} \sin\alpha^2;$$
$$\tau_{\alpha n} = 0.5(\Delta\sigma_{X(Y)} - \Delta\sigma_{Z(Y)}) \sin 2\alpha. \qquad (3)$$

Values of the residual potential stresses in the massif surrounding mine working which remained after transformation of a part of potential energy, MPa are

$$\sigma_{\alpha\beta n} = (\sigma_\alpha \sin^2\beta + \tau_\alpha \cos^2\beta)\exp(-\nu x_n);$$
$$\tau_{\alpha\beta n} = (\sigma_\alpha \cos^2\beta + \tau_\alpha \sin^2\beta)\exp(-\nu x_n), \qquad (4)$$

where *x* is a current coordinate of reference point position on the platform at angle α ($0 \le x \le A_x$) which increases from the border near-the-contour zone to the massif exposure surface of mine working, and in other energy zones – from the borders to their centers. The increment x is accepted random, but identical to all settlement platforms in each zone; ν – coefficient of absorption of elastic fluctuations, for rocks $\nu = 0.1$–0.26.

Further by computer graphics the cross section of mine working, contours of energy zones with semi-axis of a_n and b_n, according to the settlement scheme submitted in Fig. 2 [14], a is under construction. From the center of mine working, beams of the planes which correspond to angles $a \le \alpha \le 2\pi$ with the direction of stress $\Delta\sigma_{x(y}$ after 15° are conducted. Along each of them from the border of the last energy zone to the contour of mine working and the subsequent zone measure distances A_α and define values of angles β which are laid off in points of intersection of tangent lines and the contour of mine working or the border of an energy zone. Fields of residual potential radial $\sigma_{\alpha\beta}$ and tangential $\tau_{\alpha\beta}$ of stresses which remained after transformation of a part of potential energy within energy zones (Fig. 2, *b*) are built according to results of calculations.

Transition of the massif to a condition of energy disbalance is implemented in the zones which are brought closer to mine working. If in near-the-contour zone destruction causes expansion of the massif towards mine working, then in the subsequent zones – the radial-directed counter processes of divergence and convergence are developed which form ring areas of the deformed rocks in the center of zones of thermodynamic energy disbalance. In near-the-contour zone achievement of ring durability is impossible because of its unilaterality due to existence of mine working. It leads to a thermodynamic energy disbalance whose manifestations involve inrush of rocks from a roof, sides and bottom heaving, change of rock temperature, gases emission, water, etc. [15].

As a result of modelling it is established that the sizes of all subsequent energy zones regarding previous ones, including near-the-contour, have the fixed value which is constant for any mine working irrespective of its shape, depth of laying and physical properties of the massif. Calculation of conditions of laying of development and stoping mine workings at depths from 0 to 3000 m is executed at change of the modelled durability of ores and breeds from 40 to 200 MPa for checking the revealed function. Results of modelling have confirmed power law dependence of an exponential view, m

$$a_i = 0.5\, e^{0.7n}. \quad (5)$$

Mutual development of processes of convergence and divergence leads to an equilibration of elastic energy in all zones and to achievement of thermodynamic energy balance. Values of real radial σ_r and tangential τ_r of stresses acting in the massif around mine workings as a result of transformation of potential energy, are defined as a difference between the potential stresses characteristic of the undisturbed massif, and residual potential tension in points on x_i coordinate along each settlement platform respectively, MPa

$$\sigma_{pn} = \sigma_{\alpha n} - \sigma_{\alpha\beta n}; \quad \tau_{Pn} = \tau_{\alpha n} - \tau_{\alpha\beta n}. \quad (6)$$

According to σ_r and τ_r values, sizes of elastic radial ε_σ and tangential ε_τ deformations of rock within zones of thermodynamic balance are established, m

$$\varepsilon_{\sigma n} = \sigma_{pn}/E; \quad \varepsilon_{\tau n} = \tau_{pn}/E, \quad (7)$$

where ε_σ is stretching deformation; ε_τ is compression deformation.

Total values of mechanical (σ_r and τ_r), temperature (σ_t and τ_t) stresses, and also at necessity of other factors of energy intensity of the massif – density, gas-and water saturations (σ_i and τ_i,) are defined on all settlement platforms and the set x_i points, respectively, MPa

$$\sigma_{ptn} = \sigma_{pn} + \sigma_{tn} + \sigma_{in}; \quad \tau_{ptn} = \tau_{pn} + \sigma_{tn} + \sigma_{in}. \quad (8)$$

According to the results of calculations of the described above method, stresses fields σ_{pt} and τ_{pt} within zones of thermodynamic eneegy balance are built up (Fig. 1, *b*). Results of modelling have shown that for conditions of the Kryvorizskyi basin, distribution of factors of various intensity on a contour of the modelled development mine working in relation to total stresses σ_{pt} = 3.36 MPa (100 %) which by 23.7 % exceed breaking point of ore to compression (2.6 MPa) are ranged in the following order: mechanical stresses σ_p = 2.68 MPa and is equal to 80 % from general ones; temperature stresses σ_t = 0.45 MPa (about 15 %), hydro-gas stresses σ_n = = 0.22 MPa (less than 5 %) for investigated interval of rock strength and depth of mining operations.

Zone of thermodynamic balance stops to perceive full loading from compression of rocks and passes into a condition of a thermodynamic disbalance of energy when achieving breaking point of rocks to compression or stretching in the massif. Elastic deformation of the massif occurs where the actual stresses operating in the massif of a zone of a thermodynamic energy disbalance exceeds maximum permissible values for stretching or compression. The difference between the operating and extreme stresses is reflected by the coefficient of margin of safety of *n*. To define areas of elastic deformations, it is necessary to establish location of points in which coefficients of margin of safety on stretching of n_{pn} and displacement $n_{\tau n}$ will be equal to 1 on all settlement platforms. The received points divide areas of the massif in which plastic and elastic deformations in all zones of a thermodynamic energy disbalance work (Fig. 1, *c*). Development of elastic deformations in the next zone of a thermodynamic disbalance leads to formation and transferring of load of a new zone of thermodynamic balance. Thus, monitoring of all points on settlement platforms of zones of thermodynamic balance and disbalance on a condition of stretching and massif displacement is necessary for determination of quantity of power zones which, while performing conditions of $n_{pn} \leqslant 1$, $n_{\tau n} \leqslant 1$, promotes formation of new zones

$$n_{pn} = \sigma_{pgn}/\sigma_{ptn} \le 1; \quad n_{\tau n} = \tau_{gn}/\tau_{ptn} \le 1, \quad (9)$$

where strength of rocks on stretching $\sigma_{\rho g}$ and displacement$\tau_{\tau g}$ which are determined by dependence, are, MPa

$$\sigma_{\rho gn} = 0.13 K_{sw}\sigma_{comp}; \quad \tau_{gtn} = 0.15 K_{sw}\sigma_{comp}, \quad (10)$$

where K_{sw} = 0.2–0.33, coefficient of structural weakening of the massif depending on degree of a rocks cracks content.

Redistribution of stresses around mine workings stops when achieving thermodynamic balance at which durability of the zone closing the capsule will be sufficient for isolation of all zones of energy disbalance, mine working and protection from destruction of considerable volumes of the massif. Process of redistribution of energy stops, and the steady, isolated system which is called safety (isolating, protective) is formed by the capsule consisting of zones of a thermodynamic disbalance and energy balance. While modelling decrease in rock strength of σ_{comp} = 200–40 MPa and increasing mining depth of H = 0–5000 m on polynomial dependence of the fourth order, increase in quantity of energy zones in the safety capsule N = 1–5 pieces occurs.

$$N = a\sigma_{comp} H^4 - b\sigma_{comp}^{1.05} H^3 + c\sigma_{comp}^{1.094} H^2 - d\sigma_{comp}^{1.16} H, \quad (11)$$

where *a*, *b*, *c* and *d* are values of coefficients which consider changing of rock strength for conditions of the Ukrainian crystalline shield: *a* = 0.0018, *b* = 0.0116, *c* = = 0.0246, *d* = 0.0107 [8].

Laboratory research. Research on parameters of energy zones was conducted using physical models with the purpose of confirmation and visualization of the phenomenon of zone capsulation of underground mine workings. Laboratory research was carried out by means of a method of equivalent materials which has allowed visualizing primary zones, with some violation of the sizes and shapes down though. Selection of equivalent material was made by definition of strength on compression (0.60–0.70 MPa), the elasticity module (0.421 × × 10^5 MPa), the volume weight (0.16–0.20 MPa) and Poisson ratio (0.33) on cylindrical samples by means of a digital press of KC-200/EUR of the Tecnotest company (Modena, Italy). The composition of equivalent material was selected according to the main physical properties for the purpose of reproduction of properties of rocks of ore deposits of Ukraine. So, for example, properties of equivalent material regulated a ratio of quartz sand (50 %), ground granite (15 %), cast-iron shear (10 %), crushed mica (5 %) and paraffin (20 %). Optical-and-polarization materials (epoxide resin) have shown already secondary zones, but with some violation of the sizes, shapes and centerings with mine workings across and verticals. Electrowire materials (electrowire paper) have simulated primary zones, but with violation of stresses, sizes and shapes across. Definition of the position of separate zones was carried out according to the analysis of change of massif stresses. Water-parting of zones is the value of massif stresses corresponding to size γH (Table 1) as the analysis of the phenomenon of zone disintegration of rocks has shown.

Results of physical modelling have shown reliability of the relative sizes of energy zones received by means of equivalent and optical-polarization materials which made 77.5 %, optical-polarization and electrowire materials – 86.0 %, electrowire and equivalent – 96.0 %. The variability of data, received in the laboratory, varied ranging from 82.0 to 100 %, with an average reliability of 91.0 %.

Industrial research. The research of processes of zone capsulation of the massif is conducted by means of natural experiments which were made on the horizons of 665, 690 and 715 m of "Ekspluatatsiina" mine of "Zaporizskyi Iron Ore Plant" PJSC (Dneprorudny city), the horizons of 1008 and 1050 m of "Ternivska" mine, "Kryvorizskyi Iron Ore Plant" PJSC (Kryvyi Rih), the horizons of 507 and 522 m of "Smolinska" mine of "Skhidnyi Mining and Beneficiation Plant" SE (Zhovti Vody city) with usage of methods of observations and estimates, mine surveying, unloadings of the massif, boreholes deformation and deep bench marks (Table 2).

The analysis of results has shown that change of depth of contours destruction of stoping chambers changes generally on power-law dependences, and as for development mine workings adjoining to chambers – on exponential ones. Reliability of values in the received equations of depth of deformation of mine workings contours fluctuated from 88.0 to 99.0 %, with an average of 95.83 % that proves rather high precision of the obtained industrial data. Data show high reliability of change of boundary values of relative depth of massif destruction which is at the level of 81.22–86.7 %. Reliability of results within the whole range of the received sizes of depth of massif destruction is at the level of 96.0 %. Data according to thirty six development mine workings and twenty five stoping chambers located in the range of depths of 507–1008 m have allowed establishing an ellipsoidal shape of borders of contours deformation of mine workings (Table 3).

Other forms of manifestation of factors of zonal capsulation of the massif by underground mine workings were not investigated. Limits of parameter changes for calculation of values in Table 3 included conditions of laying of development and stoping workings at depths of 0–5000 m with changing of durability of ores and rocks from 40 to 200 MPa.

Technologies of underground mining with rock pressure energy usage. For assessment of relative amount of energy which can be used in technology solutions, the

Table 1

Results of measurements of energy zones during physical modelling of a massif's condition around mine workings

Method	Type of mine working	Semi-axis of energy zone, ($a_n/0.5h$) and ($b_n/0.5b$)					
		vert.	hor.	vert.	hor.	vert.	hor.
		zone № 1		zone № 2		zone № 3	
Equivalent materials	Development	1.71	1.88	γH	γH	γH	γH
	Stoping	1.71	1.51	γH	γH	γH	γH
Optical-and-polarization materials	Development	1.43	1.56	3.28	4.71	γH	γH
	Stoping	1.33	1.71	3.12	4.57	γH	γH
Conductive materials	Development	1.69	3.25	γH	γH	γH	γH
	Stoping	1.66	13.00	γH	γH	γH	γH

Table 2

Results of industrial research of massif destruction depth

Research method	Interval of investigated depths, m	Size of investigated workings, $h \times d$ and $h_k \times l_{dr}$, m	Range of massif destruction depth, U, m	Relative destruction depth, $(U + 0.5h)/0.5h$
Observations and estimations	522–1050	3.0 × 3.5	0.4–1.7	1.26–2.13
Mine surveying	640–840	35.0 × 120.0	1.0–26.0	1.06–2.48
Massif unloading	740–840	35.0 × 130.0	0.3–20.0	1.02–2.14
Boreholes deformation	975–1050	70.0 × 60.0	1.0–4.0	1.03–1.11
Deep bench marks	300–640	35.0 × 120.0	0.3–1.0	0.10–1.06

Table 3

Authenticity and precision of the obtained data

Type of research	Research method	Relative depth of massif destruction, $(U_n + 0.5h)/0.5h$	Quantity of energy zones in the massif N_n, pcs.	Relative size of energy zones, $a_n/0.5h$	Authenticity of parameter, %
Theoretical	Finite elements	–	1	1.75	85.71
			2	5.20	76.92
			3	23.00	84.21
	Thermodynamical	1.49	1	2.05	92.68
	Energetic	1.69	1	2.65	99.00
		1.49	2	5.30	
		–	3	10.60	
		–	4	21.20	
		–	5	42.40	
Average on theoretical research					87.70
Laboratory	Equivalent materials	1.14–1.50	1	1.71	94.00
	Optical-and-polarization materials	–	1	1.43	92.00
		–	2	4.71	
	Conductive materials	–	1	1.69	82.00
Average on laboratory research					89.33
Industrial	Observations and estimations	1.26–2.13	–	–	92.94
	Mine surveying	1.06–2.48	–	–	92.06
	Massif unloading	1.02–2.14	–	–	82.47
	Boreholes deformation	1.03–1.11	–	–	68.27
	Deep bench marks	1.06	–	–	–
Average on indistrial research					83.93

value of coefficient of a form of power zones λ and pressure of rocks on a contour of development of Rm was used; the design of bolting system in development mine workings and conditions of ore breaking in stoping chambers was also considered. The five teoretical-and-methodological principles suggested below allow using purposefully energy of rock massif in capsules of mine workings during underground mining of deposits with economy of resources up to 37 %. 1. The principle of counteraction to destruction of the massif means the directed usage of pressing in near-the-contour zone of safety capsule for counteraction to processes of destruction of mine working through facilities of bolting system. 2. The principle of equilibration of stability of the massif means achievement of the maximum stability of contours at certain sizes and a shape of mine workings. 3. The principle of assistance means usage of energy of the safety capsule for destruction of unstable contours of mine workings for economy of energy resources while conducting drilling-and-blasting operations. 4. The principle of elimination means elimination of mining operations from zones of a thermodynamic disbalance, allows reducing the price of mine working bolting and to increase their overall dimensions. 5. The principle of transferring means transfer of energy of destruction from near-the-contour zone of the safety capsule to the first zone of a thermodynamic disbalance. It is possible to reach total geopower effect in the form of decrease in expenses of energy and resources during mining due to sharing of several geopower principles. Energy of the safety capsule created around mine working is used on the basis of parabolic-hyperbolic dependence (Fig. 2) whose value corresponds to the principles of counteraction, equilibration, assistance, elimination and transfer of concentrated energy of the massif.

From Fig. 3 it is visible that mine working bolting by the principle of counteraction which is underlain in a support design is implemented with the energy expenses equivalent to the maximum energy generated in the massif, and while using the principle of equilibration, there is hardly any energy consumption for mine workings supporting. Beginning with the principle of assistance, it is technically feasible to use up to 10 % of energy of the massif, and for the principle of elimination up to 35 % and for the principle of transfer up to 86 %. It is possible to reach the maximum effect at purposeful usage of capsules energy of mine workings by a combination of several principles in one technology solution. So, for example, it is effective to use simultaneously a steady form and self-regulating bolting both in the face plane, and in the section of development mine workings or application of a steady form and anchor bolting for

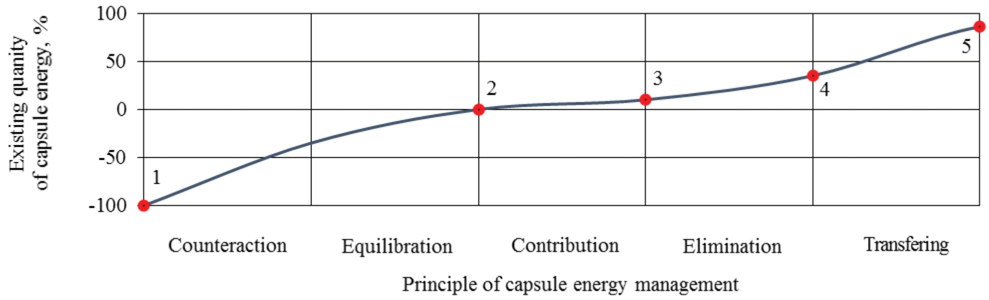


Fig. 3. Graphic interpretation of the principles of safety capsule energy management:
1–5 – key points of interaction of safety capsule energy with energy of mine working support pressing

massif exposures in stoping chambers and many other things.

The effective choice and usage of developed geopower bolting and management of the broken massif is provided with their systematization by the principles of management of safety capsule energy (counteraction, equilibration, assistance, elimination and transfer), quantity of massif energy is used in technologies (from –100 to +86 %), a type of mining operations (development, clearing), depth of mining operations (100 – 3000 m) at the mining enterprises ("Kryvorizskyi IOP" PJSC, "Zaporizskyi IOP" PJSC, "Vostochnyi MPP" SE, "Marganetskyi MPP" PJSC), which is presented in Table 4.

Conclusions and recommendations for further research.

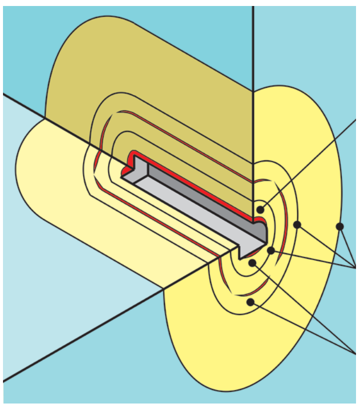
1. Quality standard of components of natural power balance which by means of entropy realizes up to 50 % of the external stresses operating in the massif of the Ukrainian crystalline shield at a depth of 1600 m is given. The research on changes of vertical and horizontal potential elastic stresses in rocks of the Kryvorizskyi Iron-ore Basin has allowed establishing the power-law dependences showing increase in a part of influence of entropy up to 95 % of the overall power balance of the external stresses operating at depths up to 3000 m.

2. Modelling of various conditions of mine workings drivage has allowed establishing the fact that the sizes and a shape of energy zones are described by system of power-law dependences. Due to change of gradients of stresses, density, temperature, gas-and-water saturations, the broken massif forms the safety capsule around mine working, whose near-the-contour zone is epicenter of development of autowave sinusoidal damped oscillations of geopower factors gradients. These processes lead to formation of ring zones of thermodynamic balance and disbalance of energy whose ratio of the sizes is described by power-law dependencies, and their quantity in the capsule as a system of polynomial dependences.

3. Examination of authenticity of the received parameters of capsulation of mine workings by the massif were conductedt using laboratory models which have shown zonal stresses of the massif, an ellipsoidal shape of zones, their centering and symmetry to mine workings with reliability of results of 89 %. The analysis of

Table 4

Parameters of safety capsule management of mine working

The 3D version of the safety capsule created around mine working	The used zone of capsule	Principle of capsule energy management	Coefficient of zone shape, λ	Pressure on a contour of working, P_m, MPa	Balance of capsule energy usage, %	Management impact on capsule
	Near-the-contour	Counteraction	0.5–0.1	> 1.75	> –100.0	Arch support of mine workings
		Equilibration	1.0–0.9	0	0	Steady sizes and shape of mine workings
		Contribution	0.9–0.8	0–0.5	0–+10.0	Destruction of unstable areas of the massif
	Boundary of zones	Elimination	0.8–0.6	0.5–1.75	+10.0–+35.0	New pathways of mine workings laying
	Neat-the-contour, first	Transfer	0.6–0.5	> 1.75	+35.0–+86.0	Self-regulating anchor support of mine workings

zone deformation areas of the massif revealed by natural research has shown that their form for development and stoping chambers aspires to ellipsoidal. Changing of depth of destruction of stoping chambers contours are described by power-law dependences, and in adjoining them to development workings – exponential dependences with reliability of results not less than 84 %.

4. Geo-energy approaches to pathways design of parameters of development and stoping mine workings in the conditions of capsulation are formulated. On their basis the principles of management of the safety capsule energy are offered: counteraction, equilibration, assistance, elimination and transfer. The share of energy of rock pressure directed to supporting of mine workings or production of minerals is described by parabolic-hyperbolic dependence that allows achieving economy of resources up to 37 % due to usage of rock pressure energy up to 86 % in technological solutions.

5. The prospect of development of the direction is development and implementation in production of technological schemes of mining of accompanying mineral deposits in low-energy areas of the safety capsules, created in mine fields with the broken distribution of massif's energy. Resource-saving technologies of ore, nonmetallic and gemstone mining will be substantiated by means of systematization of ways of management of worked-out area on mines of the Kryvorizskyi and other mining basins of Ukraine.

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Мета. Обґрунтувати принципи використанням енергії гірського тиску при підземній розробці родовищ.

Методика. Встановлення показників зонального структурування масиву навколо виробок виконано за допомогою промислових, лабораторних і теоретичних досліджень напружено-деформованого стану масиву порід. Дослідження впливу ентропії на обмін енергією та розвиток деформацій у непорушеному масиві порід виконано за допомогою ентропійного методу. Дослідження процесів формування запобіжних капсул навколо виробок і форм перетворення енергії в роботу деформування порід виконано за допомогою енергетичного методу. Розробка геоенергетичних підходів до вибору трас підготовчих виробок і розрахунку параметрів їх кріплення, а також обґрунтування параметрів проведення очисних робіт в енергетичних зонах запобіжних капсул виконані за даними оцінки ефективності геоенергетичних технологій і реалізації промислового впровадження при підземній розробці родовищ.

Результати. Розкрита фізична сутність феномену зонального капсулювання гірничих виробок. Обґрунтовані геоенергетичні принципи використання енергії гірського тиску. Створені та впроваджені у виробництво ресурсозберігаючі технології розробки родовищ.

Наукова новизна. Систематизована картина явищ, процесів і закономірностей капсулювання масивом гірських виробок з визначенням форми, розмірів, кількості енергетичних зон, синусоїдально-згасаючих напружень і кільцевих областей деформації за рахунок комплексного врахування геоенергетичних факторів, що дозволило цілеспрямовано використовувати енергію гірського тиску в технологіях розробки родовищ.

Практична значимість. Розроблена енергетична теорія прогнозування зонального капсулювання гірничих виробок, що дозволяє досліджувати параметри енергетичних зон: форми, розміри, кількість, умови утворення й межі можливого руйнування масиву. Встановлені степеневі залежності зміни розмірів суміжних енергетичних зон, співвідношення яких є константою від розмірів і форми, глибини закладення й фізичних властивостей масиву, що вміщає виробка. Удосконалена термодинамічна теорія стану непорушеного виробками масиву порід за рахунок урахування процесів перерозподілу потоків геоенергії та обміну ентропією в непорушеному масиві з виділенням в окремий метод дослідження – ентропійний. Отримала подальше уточнення синусоїдально-згасаюча залежність автохвильових коливань напружень у порушеному виробками масиві від градієнтів щільності, температури, газо- та водонасиченості гірських порід.

Ключові слова: *енергія гірського тиску, напружено-деформований стан масиву, синергетичні методи дослідження, запобіжна капсула виробки, геоенергетичні технології розробки*

Цель. Обосновать принципы использования энергии горного давления при подземной разработке месторождений.

Методика. Установление показателей зонального структурирования массива вокруг выработок выполнено с помощью промышленных, лабораторных и теоретических исследований напряженно-деформированного состояния массива пород. Исследование влияния энтропии на обмен энергией и развитие деформаций в нетронутом массиве пород выполнено с помощью энтропийного метода. Исследование процессов формирования предохранительных капсул вокруг выработок и форм преобразования энергии в работу деформирования пород выполнено с помощью энергетического метода. Разработка геоэнергетических подходов к выбору трасс подготовительных выработок и расчету параметров их крепления, а также обоснование параметров проведения очистных работ в энергетических зонах предохранительных капсул выполнены по данным оценки эффективности геоэнергетических технологий и реализации промышленного внедрения при подземной разработке месторождений.

Результаты. Раскрыта физическая сущность феномена зонального капсулирования горных выработок. Обоснованы геоэнергетические принципы использования энергии горного давления. Созданы и внедрены в производство ресурсосберегающие технологии разработки месторождений.

Научная новизна. Систематизирована картина явлений, процессов и закономерностей капсулирования массивом горных выработок с определением формы, размеров, количества энергетических зон, синусоидально-затухающих напряжений и кольцевых областей деформации за счет комплексного учета геоэнергетических факторов, позволяющих целенаправленно использовать энергию горного давления в технологиях разработки месторождений.

Практическая значимость. Разработана энергетическая теория прогнозирования зонального капсулирования горных выработок, позволяющая исследовать параметры энергетических зон: формы, размеры, количество, условия образования и границы возможного разрушения массива. Установлены степенные зависимости изменения размеров смежных энергетических зон, соотношение которых является константой от размеров и формы, глубины заложения и физических свойств массива, вмещающего выработку. Усовершенствована термодинамическая теория состояния ненарушенного выработками массива горных пород за счет учета процессов перераспределения потоков геоэнергии и обмена энтропией в ненарушенном массиве с выделением в отдельный метод исследования – энтропийный. Получила дальнейшее уточнение синусоидально-затухающая зависимость автоволновых колебаний напряжений в нарушенном выработками массиве от градиентов плотности, температуры, газо- и водонасыщенности горных пород.

Ключевые слова: *энергия горного давления, напряженно-деформированное состояние массива, синергетические методы исследования, предохранительная капсула выработки, геоэнергетические технологии разработки*

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