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A probabilistic approach to the dynamic cut-off grade assessment

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Abstract. Cut-off grade is an important conditioning parameter that determines the quantity and quality of recoverable reserves and development efficiency. Today, Russian mining companies operate with certified quality requirements. By setting permanent quality requirements, the government seeks to prevent depletion of reserves, reduced production during periods of falling prices, and decreased budget revenues, expressing the interests of all members of society. But to what extent do the permanent quality requirements protect the interests of the state? The answer to this question is ambiguous and does not lie on the surface. The State Commission for Reserves and domestic researchers are working to find a rational solution to the problem of quality requirements. One solution is dynamic quality requirements. The effectiveness of their application has been proven for individual mining companies, but it is incorrect to transfer these conclusions to the entire mineral resource base of the country.

This article presents a new approach to determining the dynamic cut-off grade, which varies depending on the price of minerals. The dynamic cut-off grade is proposed to be determined based on the indicators of constant requirements to the quality of exploration work, using the maximum allowable costs in the region. The approach allows to calculate the effect of the introduction of dynamic cut-off grade in the practice of subsurface use for the state (in the form of the amount of taxes received) and for subsoil users (in the form of the amount of income). For a group of gold-bearing deposits with open-pit mining method, it was established that the development of reserves using dynamic values of the cut-off grade in periods of price changes ensures compliance with the interests of the state and subsoil users.

***Key words*:** mineral resources base; quality requirements; dynamic cut-off grade; efficiency of mineral deposits development; probability of reserves involvement in development

Introduction. The issue of determining the cut-off grade (CG) is a key task for mining companies. It is used to delineate the ore body, to place reserves on the state register and to plan mining operations. Currently in Russia the CG is approved by the State Commission for Reserves (SCR) and is put into the feasibility study (FS) of permanent quality requirements. In all decisions on the justification and approval of quality requirements, when calculating the reserves of mineral deposits, the priority of the interests of the state as the owner of the subsurface should be considered the main criterion. By fixing permanent quality requirements, the State expresses the interests of all members of society and pursues the goal of ensuring the most complete extraction of non-renewable mineral resources. The problem of determining CG is not easy, the efficiency of development and most of the technological parameters of development depend on the optimality of the choice of CG.

Formulation of the problem. The calculation of the cut-off grade in Russia is carried out according to variant calculations. Usually, at least three variants of cut-off grades are taken, respectively, three options for delineation, calculations of efficiency indicators are carried out and the best one is selected in accordance with generally accepted criteria of economic efficiency in order to optimize the deposit development as a whole. The CG value is usually taken in the range from the minimum production to the content in the tailings of processing. This value of CG is set in FS of permanent quality requirements, determines the total reserves, the average grade in the ores of the deposit.

The choice of CG in foreign practice of subsurface use affects the profitability and viability of mining companies, the amount of available resources. Therefore, CG is the main optimized parameter [22, 42]. The cut-off grade is used for delineating ore bodies with allocation of productive strata and waste rock in the contours of mine workings [20, 24]. If the useful component is higher than CG, then the rock is classified as ore, if lower – as empty rock [21]. The main requirement for determining CG is to achieve break-even for each extracted ton of ore [4].

In foreign practice, determining the value of CG is an integral part of optimizing the production strategy, while it is considered that it should be the end result of the optimization and planning process, and not an input parameter [30, 32, 37]. At the same time, mining and processing capacities, scheduling options, cut-off grade are optimized to maximize net present value [25]. Economic criteria are excluded from consideration until a geological model is obtained that is as close to reality as possible, the principle "Geology is primary, economics is secondary" applies. Only after modeling the geological environment of the deposit do the companies proceed to the cut-off grade selection [8]. The cut-off grade is a value that the company is able to choose independently. The maximum net present value (*NPV*) is usually used as a criterion for optimizing CG [27, 35, 42]. Thus, the founder of the theory of cut-off grades K.Lane sets the task of optimizing CG from the point of view of maximizing *NPV*, taking into account three components of the mining process and three types of materials, namely, rock mass, ore and the final product [31].

In the Russian practice of subsurface use, discussions have been going on for a long time about the partial or complete rejection of fixing such an important parameter as cut-off grade. Constant cut-off grade is optimal for a specific time interval, for static economic conditions. Fluctuations in prices and costs in market conditions lead to the fact that work on fixed CG does not ensure the development of reserves according to optimal contours and does not contribute to the rational use of subsurface resources. When prices or other economic parameters change, CG needs to be revised, re-delineation and recalculation of reserves should be carried out.

To solve this problem, "Methodological recommendations on the composition and rules of registration of materials submitted for state examination on feasibility studies of quality requirements for calculating reserves of mineral deposits" (Approved by the Ministry of Natural Resources of Russia 05.06.2007) suggests the use of operational quality requirements along with permanent ones. The feasibility study of operational quality requirements is developed for a limited period (no more than 3-5 years) and applies to reserves scheduled for development during this period. The operational quality requirements may be extended for the next period upon agreement with the SCR in relation to a certain section of the subsurface. With the next change in geological or economic quality requirements, a mining company has to go through the difficult path of approving quality requirements and completely recalculating and re-approving reserves again.

As another tool for the interim re-estimation of reserves without the development of a new feasibility study, dynamic or "floating" quality requirements are proposed, which make it possible to justify the optimal cut-off grade, the amount of reserves depending on the market price of the mineral at the moment. In [11], a follower of the dynamic theory of open-pit mining, S.S.Reznichenko, presents approaches to substantiating dynamic exploration and operational quality requirements.

The justification of mineral reserves calculated according to changing operational quality requirements is presented in [6]. The dependence of the economic indicators of the main technological processes on the CG of the useful component is presented in [7]. There is an opinion that since the design and development of deposits is dynamic, the periodic updating of operational quality requirements and the refinement of reserves actually means a transition to dynamic quality requirements [13].

Most experts in the field of geological and economic assessment of deposits, including in SCR, consider the use of dynamic quality requirements (DQ) appropriate. Supporters of DQ believe that their application will allow taking into account the innovative capabilities of companies, promptly recalculating mineral reserves without detailed development of new FS quality requirements, effectively assessing the real state of the mineral resource base and forming strategies for its development [1, 3, 18]. For express determination of dynamic CG, it is proposed to use graphoanalytic dependencies [10] and a program for analytical calculation of FS quality requirements (PE Geosoft, Donetsk; LLC Zabaikalzolotoproekt, Chita) [12].

Despite this, dynamic quality requirements are not applied for a number of reasons, the main of which are the existing system of control over the use of mineral resource base (MRB) and the duration of the procedure for drawing up, reviewing and approving quality requirements [17].

In our opinion, one more, no less important reason, can be added to these ones. Dynamic quality requirements have not yet found their application, since their effectiveness for the state at the level of the mineral resource base has not been proven. A number of studies have shown the effectiveness of the use of DQ on the example of individual deposits. In [19], for the investment project of the Polymetal deposit, the damage from the inability to change the CG in a timely manner is shown. In [5] it is shown by the example of a gold deposit on the territory of the Krasnoyarsk Region that the application of the optimal cut-off grade value ensures a balance of interests of the state and the subsurface user. In [14], a type of DQ is described, which is successfully used at several deposits in China. The relationship of DQ with the capitalization of mining companies, the model and the calculation result for the Natalkinskoe gold deposit in the Magadan region are given in [1]. But it is inappropriate to transfer conclusions about the effectiveness of DQ made for individual deposits to the entire MRB. For an objective solution to the question of the effectiveness of DQ, it is necessary to make calculations for all mining companies in the country, compare the effect of development when working according to approved quality requirements and when working on DQ, depending on the price level. And only after that it is possible to conclude how justified is the introduction of DQ and dynamic CG in the practice of subsurface use.

It is not possible to carry out these calculations for all deposits that make up the MRB of a country or region using standard calculation procedures. And it is not about the complexity of calculations. Existing computer programs allow to do this quickly enough. The problem is the lack of necessary initial data for such calculations. If geological data on individual deposits can be available, then data on the costs of companies needed to calculate the profitability of development are unavailable and, often, unreliable. If an individual subsurface user can make calculations and show the effectiveness of DQ for the conditions of their deposit, then the conclusion about the effectiveness of DQ for the entire MRB is not obvious. Only if the benefits of DQ are proved not only by the example of a single deposit, but for the MRB of the country as a whole, the question of their application can be resolved positively.

This article proposes a solution for determining the dynamic CG for a group of mining companies based on the application of an approach in which the quantitative measure of the availability of mineral reserves is the probability of their involvement in development [9]. The approach has been tested on the example of various mineral resource bases, has shown adequacy in the description of real processes. The advantage of the approach is that it allows to calculate the effect of deposit development without using actual costs, using statistical estimates and values of marginal costs. The definition of CG, taking into account the marginal costs of open-pit mining, was proposed in [15]. The authors, with a known cut-off grade of useful components in the ore, estimate the amount of operating costs by calculations using analogous companies with similar development conditions. The probabilistic approach is based on other assumptions and implies the possibility of obtaining information about the object under study based on information about a set of deposits of this type. To do this, “grade-reserves” models are built, the core of which are G-T diagrams (“grade-reserves” diagrams). Such models are widely used in foreign practice, but, unlike this work, they are used to predict reserves of deposits that have not yet been explored [26, 34, 36, 39, 40], to determine the optimal CG [28, 33, 43], and highlight the economic status of deposits [38, 41]. In our article, a similar approach is used to define dynamic CG.

Theoretical model. The initial data for calculations is information on the size of ore reserves, the average grade of useful components, the number of developed and reserve objects for the same type of

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deposits with similar development conditions. The use of two factors for constructing the model – ore reserves and the average grade of the useful component is justified by studies in which it is established that for gold deposits of ore and placer deposits, copper-porphyry deposits of the world, copper-containing deposits of Russia with an open-pit mining method, reserves and grade have a significant impact on the efficiency of development. The influence of other factors is much weaker [2, 9, 16, 29]. The information is reflected in the form of a "grade – reserves" diagram. Using the logit regression procedure, the function of objects belonging to the classes of developed and undeveloped is determined, i.e. the probability of deposits being involved in development (P) depending on the size of reserves, the content of useful components in the ore,

$$P = \frac{\exp(b_0 + b_1 + b_2 S)}{1 + \exp(b_0 + b_1 + b_2 S)}, \qquad (1)$$

where b_0, b_1, b_2, – coefficients of the model; α – the average grade of the useful component in the ore, g/m^3; S – ore reserves, thousand m^3. Then a model is built for a specific regional mineral resource base, coefficients are determined, and the value of the dependent variable P is predicted. Within the framework of the model (1), the variable P will have a mathematical meaning of the probability that the deposit with the given α, S belongs to the number of those in operation.

Based on modeling the probability of development P for a set of homogeneous deposits, a number of indicators are determined.

The line of the marginal probability of development separates efficient companies from inefficient ones. The line separates a group of companies with efficiency below the limit. Such a margin can be constructed using price curves and data on the dynamics of the raw materials market. Thus, according to the Rio Tinto Mine Information System, prices on the London Metal Exchange over long time intervals fluctuate around the highest costs of mining companies, accounting for 10 % of the total number of mining companies [23]. The current costs of companies located on the line of marginal availability are closing and in the long term do not exceed market prices for mineral raw materials. The development of reserves of these deposits implies their development with zero efficiency, the costs of developing these deposits are extremely permissible.

The marginal content of the useful component in the ore (α_{marg}) is the content at which the cost of the extracted ore with the marginal content of the useful component only covers the operating costs,

$$\alpha_{marg} = KS^{-\frac{b_2}{b_1}}, \qquad (2)$$

where $K = \left[\frac{P_{marg}}{1 - P_{marg}}\right]^{\frac{1}{b_0}} e^{-\frac{b_0}{b_1}}$; P_{marg} is the marginal probability of development. Formula (2) is derived from (1) by transformations.

Effective reserves (ER) are an analogue of profitable metal reserves, are defined as the difference between total metal reserves and reserves equivalent in value to the total costs of deposit development (compensation metal),

$$\text{ER} = S(\alpha - \alpha_{marg}). \qquad (3)$$

The value of the compensation metal is defined as $S\alpha_{marg}$. The indicator calculated in kind in money terms is the equivalent of net income and shows integral income for the entire period of the deposit development.

Specific (per metal) operating development costs:

$$\text{O} = \frac{\text{C}\alpha_{marg}}{\alpha}, \qquad (4)$$

where C is the average market price for metal, USD/g.

The described model is used to solve a number of problems [2, 16, 29]. In this paper, based on a probabilistic approach, a model for calculating dynamic CG is proposed.

Presumably, the optimal CG has been calculated and approved for the field in FS of permanent exploration quality requirements (at a certain price, the productivity of the mining company and operating costs). When the price changes, this option ceases to be optimal. A decrease in price contributes to an increase in optimal CG and, accordingly, a reduction in reserves, while an increase in price implies a decrease in CG and an increase in recoverable reserves. Suppose, ore reserves adjusted as a result of price changes and revision of CG, with an average grade of the useful component a_2 and volume S_2, will be worked out with the same values (approved in FS) of specific operating costs and ore productivity. Then the new price of the final product must correspond to the value defined as

$$C_2 = O_{FS}\,\frac{\alpha_2}{\alpha_{marg2}}, \qquad (5)$$

where O_{FS} is operating costs approved in the FS, USD/g; α_2 – average gold grade when delineating of reserves by CG, other than FS, g/t; α_{marg2} – the marginal content of the useful component when delineating according to the cut-off grade, other than FS, is determined by the formula (2).

The validity of the dynamic CG calculated in this way is due to the use of indicators approved in FS for the calculation, as well as the use of maximum allowable costs for this type of raw materials determined by the probabilistic approach.

Thus, the definition of dynamic CG in the proposed approach is based on the indicators of accurate variation calculations of FS and the maximum permissible costs for the development of reserves.

Discussion. The initial data for the calculations were geological information on the same type of gold-bearing deposits with similar mining conditions, the so-called cut – off – grade – tonnage curves, which show the relationship "cut-off grade – average grade – tonnage". Information on 28 gold-bearing deposits from technical reports NI 43-101 was used. A logit regression model was constructed for gold-bearing deposits of the world with an open-pit mining method, parameter values: $b_0 = -0.94$, $b_1 = 2.86$, $b_2 = 0.48$. The model is statistically relevant, the p-level is lower than the marginal, the residues obey the normal distribution law, are not correlated with each other. For each deposit, the marginal gold content is calculated (formula (2), the price at which the processing of ores contoured according to the cut-off grade, other than FS of permanent quality requirements, is possible at the same operating costs as in FS (formula (5), effective metal reserve (formula (3), compensation metal.

Geological information and an example of calculation for one of the deposits (Ingrid Deposit) are given in Table 1. Gold reserves in the amount of 28.8 tons have been calculated and approved by the state expertise in the FS of permanent quality requirements. They are identified by CG = 0.5 g/t and ore reserves of 13.7 million tons, the average gold grade in the ore is 2.1 g/t. The cut-off grade in FS of permanent exploration quality requirements is determined at a gold price of 44.8 USD/g, operating costs 13.3 USD/g.

A reduction in the price, for example, to 37.9 USD/g will lead to the fact that with an operating cost of 13.3 USD/g, the company will be able to work out reserves contoured at CG = 0.7 g/t, while the amount of gold will decrease to 27.2 tons. The reserves approved in the FS of permanent quality requirements should be stored in special dumps for subsequent processing when the price increases. The organization of work on the creation of special dumps for storing temporarily substandard reserves may not differ from the organization of work on traditionally created average stores.

An increase in the price of gold relative to the values at which FS of permanent exploration quality requirements are approved, for example, to 58.7 USD/g, will lead to the fact that when working out reserves contoured at CG = 0.3 g/t, the company will maintain operating costs at the level approved in FS and will be able to extract 30.1 tons of metal.

During the research, various variants of changes in prices for mineral raw materials were modeled. For each variant of price change, the efficiency indicators of deposit development with constant and dynamic CG values were compared.

Table 1

Initial information and calculation result

Cut-off grade, g/t	Ore reserves, million tons	Average gold grade, g/t	Metal reserves, tons	Operating costs, USD/g	Price, USD/g	The marginal content of the useful component in the ore, g/t	Effective metal reserve, tons	Compensation metal, tons
Geological information				According to the FS	Calculation result			
0.1	21.8	1.43	31.17	13.29	92.6	0.21	26.70	4.47
0.2	19.2	1.6	30.72	13.29	69.8	0.30	24.87	5.85
0.3	17.2	1.75	30.10	13.29	58.7	0.40	23.28	6.82
0.4	15.4	1.92	29.57	13.29	50.6	0.50	21.81	7.75
0.5*	**13.7**	**2.1**	**28.77**	**13.29**	**44.8**	0.62	20.25	8.52
0.6	12.3	2.28	28.04	13.29	40.7	0.74	18.89	9.16
0.7	11.2	2.43	27.22	13.29	37.9	0.85	17.68	9.53
0.8	10.3	2.6	26.78	13.29	35.5	0.97	16.77	10.01
0.9	9.4	2.75	25.85	13.29	33.6	1.09	15.64	10.21
1	8.8	2.88	25.34	13.29	32.3	1.18	14.92	10.42

* Cut-off grade of quality requirements in FS.

Variant 1. Stable development of the mineral resource base – a sufficient number of deposits of different quality and scale have been discovered, some of them (the best from the point of view of subsurface users) are being developed. New reserves are being discovered and explored, and there is a sufficient reserve of undeveloped deposits. The metal reserves of the developed deposits throughout the MRB amount to 688 tons. Effective reserves – 380 tons. The price of metal is 44.8 USD/g.

Variant 2. The MRB parameters have not changed, there has been an increase in the price of metal by 10 % from the initial state. When working at permanent quality requirements, metal reserves will not change, but due to the price increase, the value of effective reserves will be 481 tons. When using DQ, some companies will be able to switch to lower CG values, increase reserves, and some will use old quality requirements. The previous quality requirements will be used by those companies that are already operating at the lowest possible average grade. Metal reserves throughout the MRB will increase and amount to 716 tons, effective reserves will amount to 489 tons. Thus, the result demonstrates the benefits for subsurface users and the state when working on DQ in terms of price increases.

Variant 3. Reduction of the average price level by 10 % from the initial state. Other MRB parameters have not changed. With a decrease in the price, permanent quality requirements should play a positive role and ensure the full use of the subsurface, prevent a decrease in tax revenues to the revenue side of the budget, prevent selective development of reserves and loss of minerals. Therefore, when using permanent quality requirements, the amount of extracted metal remains the same 688 tons, but due to lower prices, only 248 tons will be effective. In such a situation, subsurface users will receive significantly less income, and some of them will incur a loss, the state income will also decrease.

When working with the use of dynamic CG values, some companies will increase their maintenance and will be able to keep operating costs at the same level (FS level), some will remain operating under the same quality requirements and reduce their efficiency. The latter applies to companies the geological and economic characteristics of reserves of which do not allow to increase the average grade, i.e. they are already operating at the highest average grade. Metal reserves will be reduced to 633 tons, which will cause a reduction in the mineral extraction tax (MET). Since at the same time effective reserves will increase, this will cause an increase in income tax. In total, these two taxes (MET, income tax) will increase. In general, the MRB effect is positive both for the state and for subsurface users. Unprofitable at this price level, the metal (55 tons) will be stored in off-balance reserves and extracted with the improvement of market conditions.

The simulation results showed that when metal prices change, working with the use of permanent quality requirements is not beneficial either to the state, as the subsurface user (it will receive less taxes to the budget), or to mining companies (they will receive less profit).

The effect of using DQ for MRB was calculated for the state – as total tax revenues to the budget, for subsurface users – as total income. Income of subsurface users in Table 2 is calculated as the cost of extracted minerals minus costs.

Table 2

Efficiency of subsurface use when prices change

Indicators	Variant 1	Variant 2 (price increase by 10 %)		Variant 3 (price decrease by 10 %)	
	Initial	Permanent CG	Dynamic CG	Permanent CG	Dynamic CG
Price, USD/g	44.8	49.4		40.4	
Metal reserves, tons	688	688	716	688	633
Compensation metal, tons	308	207	227	440	369
Effective metal, tons	380	481	489	248	264
Income tax, USD million	3411	4749	4828	2003	2133
MET, USD million	1359	1494	1554	1223	1125
State revenue, USD million	4769	6243	6382	3226	3258
Income of subsurface users, USD million	17054	23745	24140	10017	10663

Conclusion. In market conditions, the problem of determining floating (dynamic, not permanent) quality requirements is especially relevant, companies must respond to changes in the market, prices, so as not to reduce the efficiency of development. Working according to quality requirements that are not optimal, permanent quality requirements, subsurface users incur losses due to the fact that reserves are not worked out optimally: either ore is not extracted, which according to outdated conditions was off-balance, or the company extracts ores that are economically unprofitable today. Permanent quality requirements are designed to protect the interests of the state as the subsurface owner. Is this really happening? The answer to this question is complex and does not allow simplified estimates based on conclusions for individual mining companies.

The existing domestic works on the calculation of dynamic quality requirements are carried out using variation calculations. They cannot be used to assess the effectiveness of DQ for the mineral resource base due to the unavailability of initial cost data. There is no concept of permanent quality requirements in the foreign practice of subsurface use. The US Bureau of Mines uses G-T models (models of mineral deposits) to optimize the cut-off grade. In the article, these models are used to calculate the dynamic cut-off grade, which varies depending on the price of the final product. An approach is proposed that allows for each option “cut-off grade – average grade – reserves” according to formula (5) to find the price at which reserves can be worked out with the cost approved in FS. In accordance with this, the option of cut-off grade is selected, which is dynamic, depending on the price. The calculation is carried out taking into account the maximum allowable costs in the region according to the probabilistic approach, based on statistical estimates. The calculations do not require actual data on the costs of existing companies or similar companies.

Using the proposed approach, the effectiveness of the use of dynamic CG for a group of gold mining companies was evaluated. It is established that if CG is set and is not a variable, then in case of price changes, the state receives less taxes from production. By changing CG, moving to dynamic CG, it is possible to reduce the negative impact of price changes. The development of reserves by dynamic CG, which varies depending on the price, ensures compliance with the interests of both the state and subsurface users. The conclusion is made not for a separate mining company, but for a group of companies developing similar deposits.

This approach can be used as a tool for evaluating the effectiveness of DQ application for the mineral resource base of a country or region upon the availability of initial data on the developed and reserve deposits of the country. The use of indicators approved in the FS and the maximum allowable costs in the region guarantee the absence of economic voluntarism in determining dynamic CG according to the proposed method.

One of the problems associated with the practical application of DQ is the effect of changes in the content of useful components in the ore on the enrichment process. This issue requires a separate solution. It should be noted here that in practice it is possible to reconfigurate the enrichment processes depending on the quality of the extracted mineral raw materials. There are examples when MPP produces and enriches two types of ores. The main thing, in our opinion, is the condition that the reconfiguration of the processing plant from one type of ore to another should take significantly less time than the period of operation with the adjusted content of the useful component. In this case this condition is met.

Another issue requiring special research is the determination of the optimal timing for revising the quality requirements. The periodicity of quality requirements adjustment can be determined based on the inertia of time series of changes in metal prices. In the studies carried out by the authors earlier, it was found that the least inertial (highly variable) are the processes of price changes for copper, nickel, zinc and lead. The time series of prices for gold, aluminum and tin, on the contrary, have a high inertia: trends in price changes persist longer. Business cycles are usually characterized by the following phases: recession, depression, recovery, expansion. The periodicity of the quality requirements revision may correspond to a quarter of the cycle of price changes for the corresponding final product. This is the starting point for determining the timing of the quality requirements revision. Determining the optimal timing of quality requirements adjustment requires additional research individually for each object and depends on the size of reserves and technology of deposit development. At the same time, the possibilities of adjusting the mining processes should be provided for in the FS of the quality requirements and FS of the deposit development.

Therefore, the use of the above approach involves the solution of a number of other related issues. These include the justification of the optimal moments when it is advisable to revise the cut-off grades, and the terms within which they will operate, as well as the planning of mining operations and inventory accounting when using dynamic quality requirements and other additional tasks. These and other issues require further research towards the development of models (1) and (5).

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