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Effect of Operating Factors on Reliability of Stoping Complexes and Assessment of Reliability of their Elements

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Abstract: For analyzing the dependence of face equipment failure on its length, two groups of elements are commonly considered. The first group includes all elements of shearer-loaders: conveyor drives, elements of pumping stations of powered supports, supports of face junctions with strikes and others. The second group includes all elements of powered support sections, linear sections of pan lines and scrapers of face scraper conveyors, electric cables of shearer-loaders, main pipelines of powered supports, etc. It is noted that the constancy of number of the first group elements linear variability of number of the second group elements do not uniquely determine the constancy or variability of the failure factor of the aggregate of the same type elements of the first or the second groups [1]. The plot of mean-time-between-failures (MTBF) of SL-500S stoping complex as function of face length is presented. Besides, the curve of the face (complex) length-dependence of average recovery) time (after failure of the SL-500S stoping complex time is shown. Analyzing the dependence of availability factor of stoping complexes on the face length showed that the length of stoping complexes is not a factor determining decrease in the MTBF and increase in the average recovery time. The plot of recovery time (after failure) of the SL-500S stoping complex as function of face length is shown. A formula is presented for assessing the cumulative effect, on the MTBF of SL-500S stoping complex, of its length and potash ore cuttability. The plot of correlation between the MTBF of SL-500S stoping complex and the face length/the potash ore cuttability is presented, which demonstrates that the complex length followed by the thickness of the extracted layer produce the greatest effect on the MTBF. The plot of the number of failures per day as a function of the maintenance factor of the SL-500C shearer-loader is presented. The plot demonstrates that the average number of failures of the SL-500C shearer-loader per day reaches a minimum and practically stabilize at values of the maintenance factor of 0.9–1.0, which correspond to three-shift production with one 6-hour maintenance shift per day.

Keywords: production face, stoping complex, face equipment, running hours, failure, recovery time, correlation coefficient, face length, thickness of extracted layer.

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Влияние эксплуатационных факторов на надежность очистных комплексов и оценка надежности их элементов

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Аннотация: В целях анализа зависимости на отказ забойного оборудования от его длины обычно рассматриваются две группы элементов. К первой группе отнесены все элементы очистных комбайнов: приводы конвейеров, элементы насосных станций механизированных крепей, крепей сопряжений лавы со штреками и другие. Ко второй группе относятся все элементы секций механизированной крепи, линейные секции рештачного става и скребки забойных скребковых конвейеров, электрические кабели комбайнов, магистральные трубопроводы механизированных крепей и т.п. Отмечено, что постоянство числа элементов первой группы или изменчивость по линейному закону числа элементов второй группы не определяют однозначно постоянство или изменчивость величины параметра потока отказов совокупности однотипных элементов первой (ω_{cI}) или второй (ω_{cII}) групп [1]. Представлен график зависимости времени наработки на отказ очистного комплекса СЛ-500С. В общем виде представлена зависимость величины среднего времени восстановления комплекса от его длины. Анализ зависимости коэффициента готовности очистных комплексов от длины лавы показал, что длина очистных комплексов не является фактором, определяющим степень снижения наработки на отказ и увеличения среднего времени восстановления. Проиллюстрирован график зависимости времени восстановления отказов очистного комплекса СЛ-500С от длины лавы. Представлена формула для оценки совместного влияния на наработку на отказ очистного комплекса, его длины и сопротивляемости калийной руды резанию. Приведен график корреляционной связи между наработкой на отказ комплекса СЛ-500С от длины лавы и сопротивляемостью калийных руд резанию, из которого видно, что наибольшее влияние на величину наработки на отказ очистных комплексов оказывает их длина, а затем и мощность вынимаемого пласта. Представлен график изменения количества отказов в сутки в зависимости от коэффициента технического обслуживания очистного комбайна СЛ-500С, из которого следует, что среднее количество отказов очистного комплекса СЛ-500С в сутки достигает минимума и практически стабилизируется при значениях коэффициента технического обслуживания 0,9–1,0, что соответствует трехсменному режиму по добыче и одной 6-часовой ремонтной смене в сутки.

Ключевые слова: очистной забой, очистной комплекс, забойное оборудование, наработка, отказ, время восстановления, коэффициент корреляции, длина лавы, мощность вынимаемого пласта.

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Introduction

Stoping mechanical equipment at potash mines has undergone significant quantitative and qualitative changes in recent years. Their development expanded from mechanization of certain basic operations of mineral extraction process in a face to complex mechanization and automation of the entire technical process. Integrated mechanization and automation of all processes of potash ore mining provides for the interaction and simultaneous operation of various machines and mechanisms united in a single technological process. Due to availability of many components and sequence of the equipment operation, insufficient reliability of individual machines and mechanisms leads to decreasing the useful (machine) operating time of the entire longwall set of equipment (LSE) [2]. The failure of any of the mechanisms of the LSE leads, as a rule, to complete stop of stoping in the face, therefore, the requirements for the reliability of each mechanism of the LSE are significantly increased.

Failures of stoping equipment (stoping machines, powered support, scraper conveyors) for the most part occurs during short-term single static and dynamic loading or long-term static loading. Fatigue failures caused by prolonged action of alternating-sign loads occur less frequently. This is due to the fact that stoping equipment is subject to high loads, which leads to the destruction of parts under stresses exceeding their endurance limit.

The main function of stoping facilities is the production of potash ore with the required productivity, determined based on the condition of ensuring a given load on ta production face and labor productivity of workers.

The effect of longwall face length on the level of reliability of longwall sets of equipment. Improving the mining sector and increasing the economic performance of potash mines is connected with permanent increasing length of the production faces, and, consequently, the length of longwall sets of equipment. As changing the length of the stoping equipment leads to changing length of the scraper chains of conveyors, the number of linear sections of their pan lines and sections of powered supports, as well as the operation mode of various elements, the reliability indicators of the same type face equipment will not remain constant [3].

For analyzing the dependence of face equipment mean-time-between-failures (MTBF) T on its length L, two or three groups of elements are usually considered [4], namely: elements whose number changes stepwise with significant change in the length of longwall sets of equipment, and elements whose number and length change in direct proportion to L.

The first group includes all elements of shearers (with the exception of electric cables), conveyor drives, elements of pumping stations for powered support, support for longwall face junction with drifts and other.

Total number of the first group elements:

$$N_{\mathrm{I}}(L)=\sum_{i=1}^{ч_{\mathrm{I}}} N_i = \mathrm{const}, \qquad (1)$$

where N_i – is the number of elements of the i-th type; $ч_{\mathrm{I}}$ – the number of types of elements quantity of which is independent of L.

The second group includes all elements of powered support sections, linear sections of pan lines and scrapers of face scraper conveyors, electric cables of shearers, main pipelines of powered support, etc. [5].

The number of second group elements is dependent on the face equipment length by expression:

$$N_{\mathrm{II}}(L)=\sum_{j=1}^{ч_{\mathrm{II}}} K_j L, \qquad (2)$$

where $K_j = \Delta N_j$ is coefficient of proportionality of changing total number of elements of the j-th type (for linear elements $K_j = 1$); $ч_{\mathrm{II}}$ – the number of types of elements, quantity and length of which varies proportionally to L.

It should be noted that the constancy of number of the first group elements, or the linear variability of number of the second group elements do not uniquely determine the constancy or variability of the failure factor for the assembly of the same type elements of the first (ω_{cI})or second (ω_{cII}) groups [1]. The condition $\omega_{\mathrm{cI}} = \omega_i N_i = \mathrm{const}$ will be met if $\omega_i = \mathrm{const}$, which in turn is also determined by the mode of operation of the elements, which may deteriorate, improve, or remain unchanged with the growth of L [6].

The loading modes of the elements of shearers, with neglect of certain change in the their work dynamics can be considered practically independent of L, that is, in this case the condition $\omega_{\mathrm{cI}} = \omega_i N_i = \mathrm{const}$ is met. The value of the sudden failure factor of shearer electric cables normalized to 1 linear meter is also independent of L [7]. But due to the fact that the length of such elements varies in direct proportion to L, the failure factor for a combination of such elements is function of L, that is $\omega_{\mathrm{cII}} = \omega_j L$. The magnitude of the load of traction chains and drives of face scraper conveyors increases with growth of L, therefore, for the former, $\omega_{\mathrm{cII}} = \omega_j(L)$, and for the latter, $\omega_{\mathrm{cII}} = \omega_j(L) N_j$. With growth of L, the duration of the load on the elements of the powered support sections, which ensures operation of the roof-supporting sections, will increase. For this case, $\omega_{\mathrm{cII}} = \omega_j(L)\Delta N_j L$.

For elements of cyclic action, when the number of working cycles per unit time of effective operation of the longwall set of equipment [8] is inversely proportional to L, and the total number of elements increases in direct proportion to L, the failure factor of the aggregate of the same type elements remains unchanged. For example, the value ω_{c} for back-flow valves of the support valve of a hydraulic prop, the sections of which move after the shearer passage, does not depend on L and is equal to expression

$$\omega_c = \frac{60V_п}{\bar{n}_{пер}L}\Delta NL\,, \tag{3}$$

where $V_п$ is the shearer axis velocity, m/min;

L – face length, m;

$\bar{n}_{пер}$ – MTBF of back-flow valve, measured by the number of movements of the support sections;

ΔN – the number of elements per 1 linear meter of the longwall set of equipment length.

In the general case, one can imagine

$$T(L) = \frac{1}{\sum_{i=1}^{ч_\alpha}\omega_{ci} + \sum_{j=1}^{ч_\alpha}\omega_{cj}(L)}, \tag{4}$$

where ω_{ci} and ω_{cj} are the values of the failure factors for the assembly of elements of the i-th or j-th structural types;

$ч_\alpha$ – the number of types of elements for which $\omega_{ci} = \text{const}$;

ω_{cj} – the number of types of elements for which $\omega_{cj} = \phi(L)$.

In this case, it is understood that the ω_{ci} and ω_{cj} values are constant in time t.

The task of determining quantitative dependencies $T(L)$ for different types of face equipment systems was solved using correlation analysis. The obtained empirical dependences for longwall sets of equipment with narrow-web shearers for layer-by-layer and bulk (Fig. 1) extraction are described by the hyperbole equation of the form [9], min,

$$T(L) = \frac{\alpha}{L - C} + в. \tag{5}$$

The values of indicators a, в and C (Table 1) were obtained by the algorithm and the computer program.

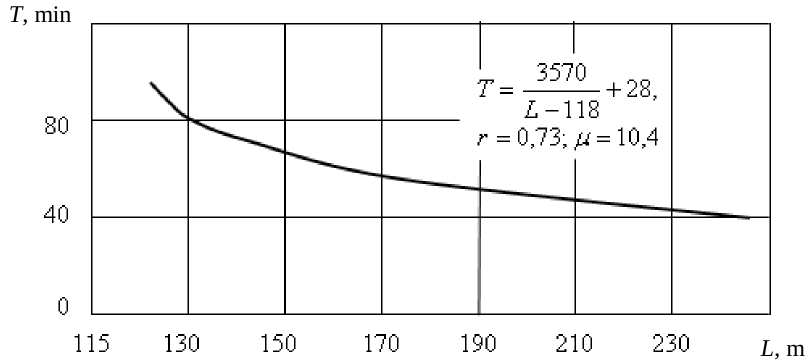

Fig. 1. Mean-time-between-failures of SL-500S stoping complex as function of face length

Table 1

Parameters of formula (5) and the correlation coefficient reliability indicators

Face equipment	Measurement limits L, m	Parameter value			Correlation ratio r	Reliability of correlation ratio μ
		α	в	C		
SL-500S	150…250	1070	28	118	0.73	10.4

The values of the obtained correlation ratios given in Table 1 indicate good correlation between T and L.

According to Lyapunov's theorem [3, 4], if $\mu \geq 3$, it can be argued that the relationship between the studied quantities is reliable and the $T(L)$ dependence is objective.

To establish the nature of the dependence of the average recovery time of a longwall set of equipment on its length, it is also advisable to consider two types of failures, the duration of the elimination of which does not depend on L. The time for eliminating failures of the end elements of longwall set of equipment on the side of the stoping face, where the repairman (duty wireman) is usually located, does not depend on the length [10, 11]. The time for eliminating failures of the longwall set of equipment elements, when no spare parts or special tools are required, also practically does not depend on L. This may include failures such as "a shearer – conveyor misalignment", "tilt" and "skew" of a support section. Such failures are usually eliminated by the stoping face workers, or they are liquidated without waiting for the repairman to arrive.

In general terms, the dependence of the average recovery time of a longwall set of equipment on its length is given by

$$T_{\text{в}}(L) = \frac{\sum_{i=1}^{n_i} t_{\text{в}i} + \sum_{j=1}^{n_j} t_{\text{в}j\text{пост}} + \sum_{j=1}^{n_j} t_{\text{в}j}(L)}{n_i + n_j}, \qquad (6)$$

where $t_{\text{в}i}$ – is the time of eliminating the i-th failure, when the time is independent of L;

$t_{\text{в}j\text{пост}}$ – a constant component of the failure eliminating time, when the time depends on L;

$t_{\text{в}j}(L)$ – the variable component of the j-th failure eliminating time;

n_i, n_j – the total number of failures of the i-th and j-th types.

The constant component of the j- th failure eliminating time $t_{\text{в}j\text{пост}}$ includes the time of repair or replacement of an element, as well as the time spent on testing equipment after the repair and downtime for organizational reasons.

The variable component $t_{\text{в}j}(L)$ takes into account the time spent on failure detection, consisting of the time the repairman moves along the face and the failure search, and the time for the necessary spare part delivery. Changing the variable component of the j-type failure elimination time is described by the following expression:

$$t_{\text{в}j}(L) = \frac{\alpha}{V_{\text{раб}}} L + \Delta t_{\text{в}j}(L), \qquad (7)$$

where $V_{\text{раб}}$ – the average repairman velocity of travel along the face;

$\Delta t_{\text{в}j}(L)$ – additional time for the spare part delivery, not combined with the repairman traveling;

α – coefficient taking into account the most probable way of the repairman traveling.

For existing longwall sets of equipment, for the face equipment element failure elimination, the value α can be taken equal to 0.5.

Experimental studies have shown that for longwall set of equipment the dependence of the average recovery time on the longwall face length is rectilinear (Fig. 2), min,

$$T_{\text{в}} = \alpha + eL. \qquad (8)$$

The values of α and e parameters in formula (8) for the investigated types of the face equipment, as well as the obtained values of the correlation coefficients r and reliability indicators of the correlation coefficients μ are shown in Table 2.

Table 2

Parameters of formula (8) and the correlation coefficient reliability indicators

Face equipment	Measurement limits *L*, m	Parameter value		Correlation coefficient *r*	Correlation coefficient reliability μ
		α	*e*		
SL-500S	150…250	−22	0.31	0.53	3.7

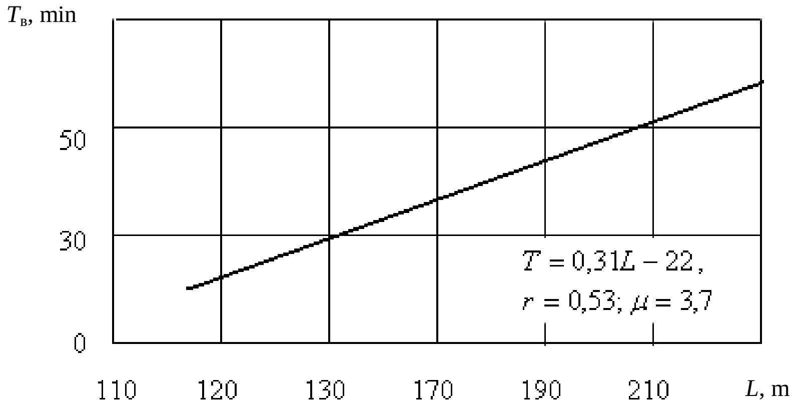

Fig. 2. SL-500S stoping complex recovery time ($T_в$) (after failure) as function of face length (*L*)

Decreasing the MTBF and an increasing the average recovery time with growth of *L* results in decreasing the availability factor (9), as

$$K_r(L)=\frac{T(L)}{T(L)+T_в(L)}. \qquad (9)$$

An analysis of the dependence of the availability factor of longwall sets of equipment on the face length showed that the LSE length is not a factor that uniquely determines the degree decreasing the MTBF and increasing the average recovery time.

Influence of potash ore cuttability and layer thickness on the face equipment reliability.

When extracting potash ore by longwall set of equipment, the main factor restraining the production development is rock cuttability A, kN/m [13].

Using the pair correlation method allowed determining a relationship between the MTBF and the average recovery time of face equipment on the one hand, and individual mining, geotechnical, and geological factors on the other hand.

To determine the joint effect of a number of factors on one dependent variable, the multiple correlation method was used, which makes it possible to identify the joint effect of a combination of the listed factors on face equipment reliability, to separate the major factors from the minor ones, and to determine the contribution of different factors in the formation of reliability indicators.

The SL-500S longwall set of equipment factors variation limits, their average values, and standard deviations are given in Table 3.

The joint effect of a longwall set of equipment length and potash ore cuttability on the MTBF is estimated by formula, min,

$$T=\frac{17100}{L}+\frac{2200}{A-75}-59, \qquad (10)$$

at $R_{T,L,A}=0{,}65\pm0{,}065$; $R_{T,\,L,\,A}=$ $0{,}65\pm0{,}065$; $d=0{,}42$; $\mu=9{,}6$.

Table 3

Determination of the SL-500S stoping complex factors variation limits

Factor description	**UoM**	**Average factor value**	**Factor variation range**
Face length $L_л$, m	150	126–250	33
Potash ore cuttability A, kN/m	265	128–196	20

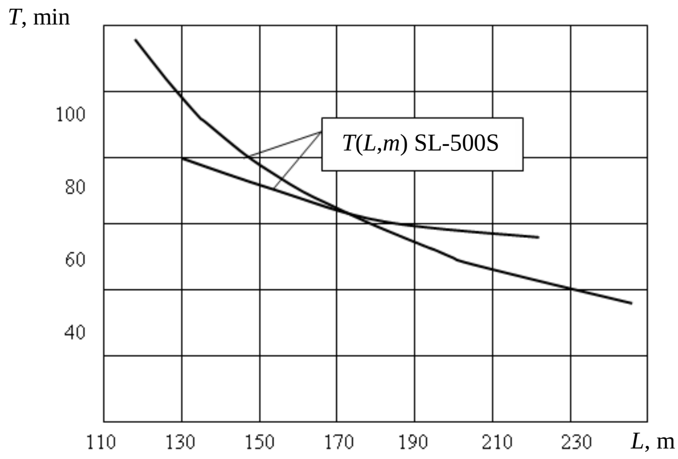

Fig. 3. Correlation between the mean-time-between-failures of SL-500S stoping complex and the face length/the potash ore cuttability

The high values of the multiple correlation coefficients R and the determination coefficients d in the equations indicate that the major factors that influence the MTBF of the considered types of face equipment are taken into account and the relationship T with mining, geotechnical, and geological conditions of LSE operation are effectively reflected [14].

To determine the degree of influence of each of the considered factors on the MTBF of the SL-500S longwall set of equipment based on correlation equations (10), specific correlation equations of the relationship between the studied attributes were found [15]. At average values of the arguments (attributes) listed in Table 3, the specific equations for the SL-500S LSE are as follows, min,

$$T(L) = \frac{3050}{L-93} + 10, \quad (11)$$

$$T(A) = \frac{2100}{A-80} + 12. \quad (12)$$

The graphs constructed based on equations (11), (12) are shown in Fig. 3.

The graph obviously demonstrates that the LSE length followed by the thickness of the extracted layer produce the greatest effect on the MTBF.

The joint influence of the considered factors on the average recovery time for the SL-500S LSE is characterized by correlation equations, min,

$$T_в = 0{,}3L - 23m - 1, \quad (13)$$

at $R = 0{,}65\ldots0{,}14;\ \mu = 6{,}2;\ d = 0{,}42$.

From equation (13), specific correlation equations can be obtained, which have the following form for the SL-500S LSE, min,

$$T_в(L) = 0{,}3L - 16, \quad (14)$$

$$T_в(m) = 66 - 23m. \quad (15)$$

An analysis of equations (14), (15) shows that, same to the case of MTBF, the face length is the factor that has the most significant effect on the average recovery time of the face equipment.

Influence of a stoping face operation condition on reliability of the face equipment.

It was found that the probability of failure-free operation of a LSE decreases with increasing intermaintenance period. In [16], it is indicated that the number of gradual failures of the face equipment is significantly affected by the intermaintenance period and the labor input of a maintenance team (man-hour). The probability of wear-out failures at different maintenance team man-hour values and maintenance frequency for the SL-500S longwall set of equipment can be assessed using the data given in Table 4.

Processing of statistical data for the SL-500S LSE made it possible to obtain a maintenance factor $K_{\text{ТО}}$ and determine the number of failures [17] that occur for a day, the analysis of which showed that the stoping face operation condition/mode significantly affects the LSE reliability.

The correlation equation for the relationship between the number of failures per day $n_{\text{сут}}$ and the factor $K_{\text{ТО}}$ value is given by:

$$n_{\text{сут}} = \frac{5{,}1}{K_{\text{ТО}} + 0{,}5} - 0{,}6, \qquad (16)$$

at $K_{\text{ТО}} = 0 - 1{,}22$; $r = 0{,}74$; $\mu = 8{,}3$ and maintenance labor input equal to 18–24 man-hour.

The number of failures per day as function of maintenance factor of SL-500S longwall set of equipment is shown in Fig. 4.

Table 4

Probability of wear-out failures at different maintenance man-hour values and maintenance frequency for the SL-500S stoping complex

Maintenance team labour input, man-hours	Probability of wear-out failures during intermaintenance period $t_{\text{мр}}$, h			
	18	42	66	144
18	0.030	0.080	0.145	0.495
30	0.010	0.035	0.095	0.245
42	0.001	0.010	0.020	0.115

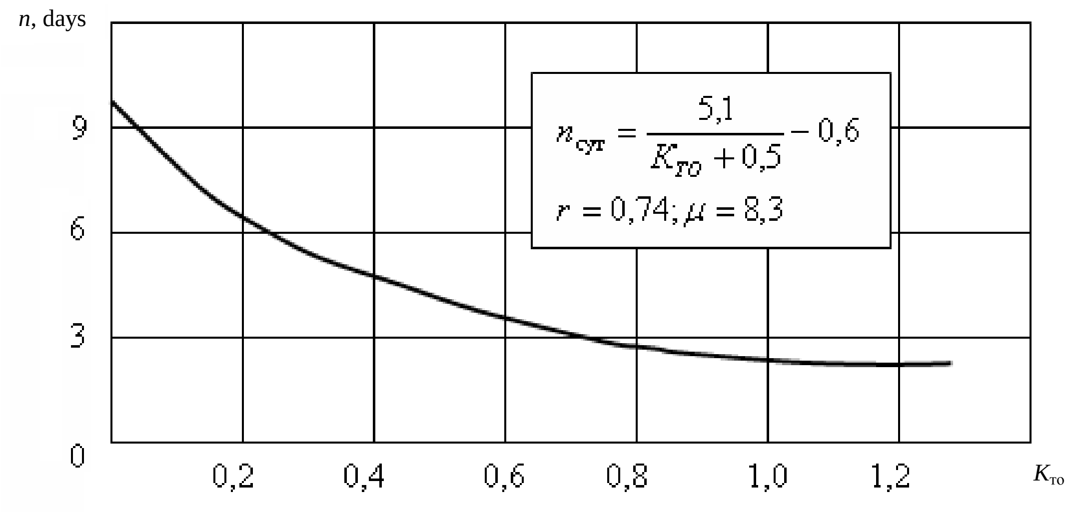

Fig. 4. Number of failures per day as function of maintenance factor of SL-500S stoping complex

The graph in Fig. 4 demonstrates that the average number of failures of the SL-500S LSE per day reaches a minimum and practically stabilizes at values of the maintenance factor $K_{ТО} = 0.9 - 1.0$ that correspond to three-shift production mode with one 6-hour maintenance shift per day. The studies allowed establishing that for different types of face equipment there exist a limit of increasing the average intermaintenance period at the expense of increasing the maintenance team labor input (man-hour). This limit depends on complexity of the equipment used [18, 19].

Conclusion

Among the mining and geological factors, the most significant impact on LSE shearer faultless performance is produced by the potash ore cuttability, and on reliability of the LSE as a whole, by the thickness. Increasing these parameters results in decreasing the face equipment MTBF. The average face equipment recovery time decreases with increasing the layer thickness.

The change in the failure factor of complex face equipment depending on its mechanical life is characterized in the general case by a sequence of typical diagrams with increasing value of the failure factor in stationary sections.

Analyzing the dependence of availability factor of longwall set of equipment on the face length showed that the LSE length is not a factor determining decrease in the MTBF and increase in the average recovery time [20].

The studies allowed establishing that for different types of face equipment there exists a limit of increasing the average intermaintenance period at the expense of increasing the maintenance team labor input (man-hour).

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