UDC 621.314.26:622.647.2
DOI: 10.15587/1729-4061.2016.75936

# THE IMPACT OF AN UNEVEN LOADING OF A BELT CONVEYOR ON THE LOADING OF DRIVE MOTORS AND ENERGY CONSUMPTION IN TRANSPORTATION

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***Об'єктом дослідження є процес транспортування гірничої маси стрічковим конвеєром при інтенсивному вуглевидобутку. Предмет дослідження – закономірності впливу нерівномірності вантажопотоку на енергетичні параметри транспортування і ресурс стрічкового конвеєра в умовах інтенсивного вуглевидобутку. Встановлено суттєву нерівномірність вантажопотоку, маси вантажу, що транспортується, та їх вплив на величину і характер нерівномірності навантаженості двигунів приводу, а також питомі енерговитрати на транспортування і ресурс конвеєра. Використання отриманих результатів сприятиме створенню шахтних стрічкових конвеєрів для високоефективного інтенсивного вуглевидобутку***

***Ключові слова: інтенсифікація вуглевидобутку, конвеєр, вантажопотік, маса вантажу, енерговитрати***

***Объектом исследования являются процессы транспортирования горной массы ленточным конвейером при интенсивной угледобыче. Предмет исследования – закономерности влияния неравномерности грузопотока на энергетические параметры транспортирования и ресурс ленточного конвейера в условиях интенсивной угледобычи. Установлена существенная неравномерность грузопотока, массы транспортируемого груза на ленте и их влияние на величину и характер неравномерности нагруженности двигателей привода, а также удельные энергозатраты на транспортирование и ресурс конвейера. Использование полученных результатов будет способствовать созданию шахтных конвейеров для высокоэффективной интенсивной угледобычи***

***Ключевые слова: интенсификация угледобычи, конвейер, грузопоток, масса груза, энергозатраты***

## 1. Introduction

One of the directions in developing modern coal mines is intensification of coal mining in order to improve productivity and reduce the cost of mining. This causes a decrease in the number and an increase in the length of mine faces, improving the performance and power capacity of the involved machines. A significant role in intensifying coal mining is played by underground transport the costs of which can exceed 40 % of the cost of production. Therefore, it is important to increase the efficiency of the transportation means of a mining enterprise [1].

Currently, belt conveyors are one of the most important links in the transport system of coal mines. Belt conveyors are characterized by flexibility, high performance at a great length and a relatively low transport capacity, smooth and quiet running, ease of automation, a possibility to create assembly lines, including branched lines, low metal content, a possibility to transport people, etc. [2]. Thus, improving the efficiency and the technical level of belt conveyors is an important part of intensifying coal mining at mining enterprises.

One of the ways to increase the efficiency of conveyor transport is to reduce the cost of transporting the mined bulk [3]. The present study is devoted to finding ways to reduce energy costs and to increase the conveyor resource at variable load flows by determining the patterns of influence of an uneven load weight on these parameters as well as by obtaining source data for designing highly efficient mine transport. It is important to reduce energy consumption and to improve the conveyor resource in order to reduce production costs. Even when the cost of mining raw materials is reduced by 5 % at an average annual production rate of 6 million tonnes of coal and the cost of UAH 1.5 thousand per tonne, it is possible to achieve an annual economic benefit of UAH 450 million.

## 2. Literature review and problem statement

The most universal indicator of energy efficiency of a transport unit is the parameter of specific energy consumption E that denotes energy consumption for transporting 1 tonne of a load by a belt across a distance of 1 km, which is determined by the formula:

$$E = \frac{N}{Q_{av}L} \text{ kW·h /(t·km)}, \tag{1}$$

where N is energy consumption, kW; $Q_{av}$ is the average load flow, t/h; L is the length of the conveyor, km.

In real conditions, the amount of the consumed energy and the average load flow corresponding to the current value of the load weight on the conveyor change during the operation of the transport machinery. For a proper evaluation of specific energy consumption for transporting the load by an underground conveyor belt, it is reasonable to use data obtained in representative conditions of mines having modern treatment and tunnel complexes.

The dependence of energy consumption for transporting loads by conveyor belts on the load flow has been researched since the second half of the 1960s [4]. The studies have been based on the results of a chronometry monitoring of the process of loading coal into mine trolleys of a trunkline transport. The considered sources of load flows have been the cutter-loaders 1K-52Sh, MK-64, and LGD-1 as well as the plough units USB-2M. Since these machines are now out of production, it is necessary to conduct further research on the characteristics of mine flows generated by modern high-performance cutter-loaders and road headers.

It should be noted that even if it has been proven that scraper conveyors require speed regulation [5–9] the question of the advisability and a rational algorithm of the drawbar organ speed control is still insufficiently studied for belt conveyors to ensure, as a rule, transportation of loads under an intensive extraction of coal from multiple faces. Contemporary researchers of this problem provide various results on evaluating energy efficiency of belt conveyors with variable drives [10–13]. There is also a problem with the assessment of the statistical characteristics of load flows in mine conveyor transport that directly determine the result of calculating their energy efficiency and resource, including the result for mine belt conveyors with variable drives [14].

Currently, there are no sufficient experimental data on the energy characteristics of modern belt conveyors of mines equipped with high-performance extraction complexes. Obtaining and further accumulation of data of experimental studies of load flows and energy performance of conveyor transport while using these systems can be the way to increase the efficiency of their use and to intensify production.

## 3. The aim and tasks of the study

The aim of the study is to determine the influence of the conveyor belt loading on the loading of its drive, energy consumption and the conveyor resource to create a highly efficient mine transport for intensive extraction of coal.

To achieve the goal, it is necessary to solve the following tasks:

– to evaluate the dynamism of loading the drive motor, which characterizes the capacity of the belt conveyor;

– to determine the uneven rate of the mined bulk and its impact on the workload of the belt, the influence of the latter on the capacity developed by the drive motors of the belt conveyor as well as energy performance in an idle mode and load transportation;

– to clarify experimentally the drag factor of the belt movement in representative conditions of intensive mining;

– to use the results of experimental studies to make recommendations for maintaining a constant load of the conveyor belt along the whole length and in terms of the receiving capacity.

## 4. Research materials and methods

### 4. 1. The experimental setup

Assessment of the energy performance of the conveyor was carried out on the basis of the results of experimental studies of load flows and the drive capacity conducted by the Dongiprovuglemach institute (Ukraine) for the belt conveyor 2LU120V (No. 4) of the eastern conveyor line of the Dovzhanska-Capital mine of the LLC DTEK Sverdlovanthracite (Sverdlovsk, Ukraine). The eastern conveyor line transports the mined bulk of two working faces equipped with the complexes MKD80 and MKD90 and one preparatory face. The parameters are the following: the conveyor length is L=730 m, the belt speed is v=2 m/s, the rated capacity of the drive is $N_{dr}$=2×250=500 kW, the maximum capacity is $Q_{max}$=1500 t/h, the belt is 2RTLO2500, the transportation angle is β=3°, and the transportation is from top to bottom. The capacity developed by the motors is measured at their input terminals. The load volume was assessed by the readings of a removable tensiometer located in the upper branch of the conveyor unloading boom. The conveyor is equipped with a tight winchdown tensioner.

The flowchart of the experimental procedure is shown in Fig. 1. The results of the experimental data obtained in 2013 and 2014 are presented in [15, 16]. They reflect the obtained arrays of current load values on the tensiometric bearing **Q** and the consumed energy **N**. The experiment duration is T=17 hours, with the readings interval Δt=1 s and the number of readings k==3600T/(Δt)=61,200 s.

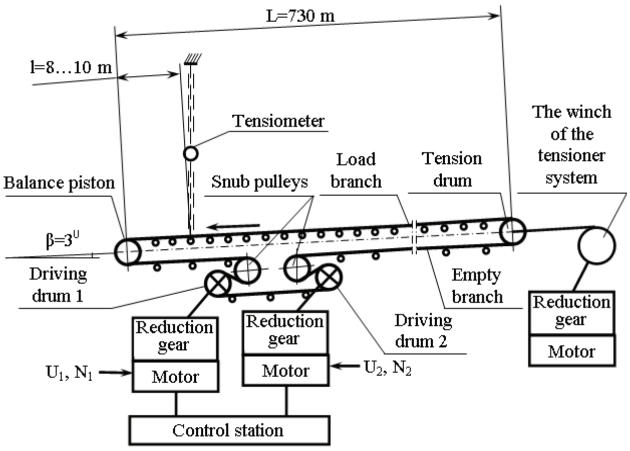


Fig. 1. The flowchart of experimental studies of the capacity developed by the drive motors for the conveyor 2LU120V (No. 4) of the eastern conveyor line of the Dovzhanska-Capital mine of the LLC DTEK Sverdlovanthracite (Sverdlovsk, Ukraine): L is the transportation length, l is the distance from the balance piston axis to the point of the installed sensors on the balance console, Q is the load flow, v is the belt speed, $U_1$ and $U_2$ are the voltage volumes applied to the drive motors $D_1$ and $D_2$, whereas $N_1$, and $N_2$ are the capacities developed by the drive motors $D_1$ and $D_2$

## 4. 2. The methodology and procedure of the study

The weight of the load placed on the conveyor belt at a moment of time t:

$$W(t)=\int_{t'=t+t_1}^{t+t_1+t_2} Q(t')dt,\ \ t, \qquad (2)$$

where $t_1$ and $t_2$ are time indicators of the load passing from the place of weighing it up and the loading place to the place of unloading, respectively; $Q(t')$ is the current experimental value of the load flow.

The value of the transported load on the conveyor belt at the current time is:

$$W(t_i)=0.001\sum_{k=i+6}^{i+371} Q_k,$$
$$i\in[4...(3.600T/(\Delta t)-365)],\ \ t, \qquad (3)$$

where $Q_k$ is the value of the load weight on the tensiometer roll bearing at the time $t_k=k\cdot\Delta t$, kg/s.

The nature of the changes in the capacities $N_1$ and $N_2$ developed by the drive motors and determined in experimental studies and their respective load weights W on the conveyor according to the dependence (3) is shown in Fig. 2. The analysis of the curves reveals a significant effect of the weight of the transported load on the capacities developed by the drive motors. In the cases of idling and load transportation, the capacity of one drive motor of a belt conveyor ranges from 70 kW to 180 kW, and its value depends on the weight value of the load transported by the conveyor. The start-up power that is developed by the drive motors amounts to 380 kW.

In order to determine the type of the electric drive motors loading and the dependence of the capacities developed by them on the weight of the transported load, the capacities developed by the drive motors were registered in experimental trials and subjected to a regression analysis. To select the optimal mode of the belt conveyor drive, specific energy consumption for transporting 1 tonne of the load was determined for a distance of 1 km at a varying weight of the load transported on the belt. Data were specified for calculating the traction of the belt conveyor according to the standard procedure.

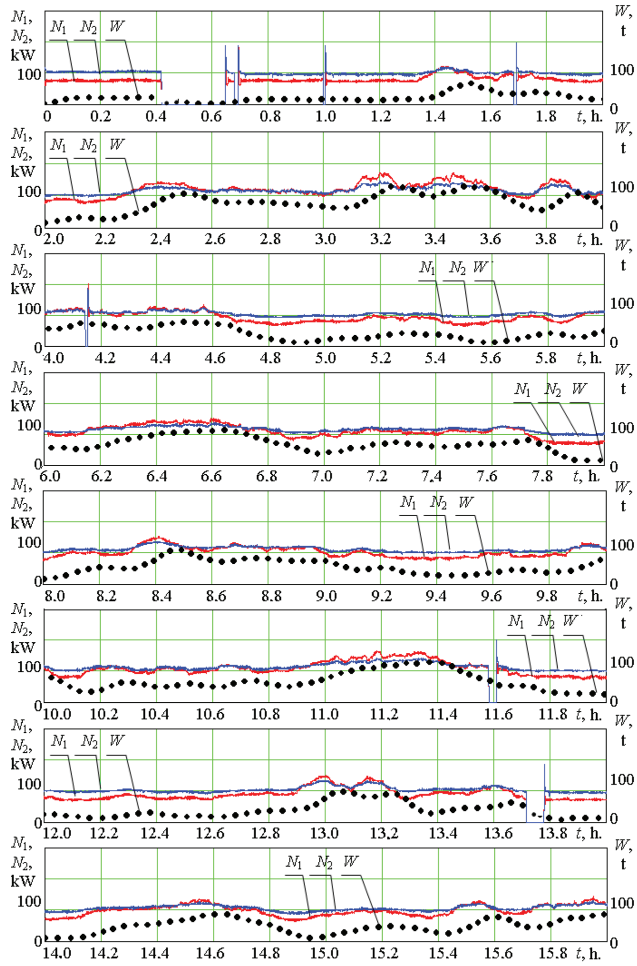


Fig. 2. Changes in the capacity of the drive motors $N_1$ (the red line) and $N_2$ (the blue line) and the weight W of the load on the belt (the black marker) at a long-term operation of the belt conveyor 2LU120V of the eastern conveyor line of the Dovzhanska-Capital mine

## 5. The results of the experiment to establish the influence of the unevenness of the load flow and the belt loading on the drive loading

The regression dependence of the conveyor system capacity on the load weight on the belt is the following [16]:

$$N_i=N_0+\Delta N_W\cdot W_i\ \ kW, \qquad (4)$$

where $N_0=160$ kW is the capacity of an idle conveyor, kW; $\Delta N_W=1.1$ kW/t is the increment of the consumed capacity at increasing the weight of the load on the belt by 1 tonne.

The uneven loading of the electric motors in terms of their capacity is determined by the ratio factor of the capacities of the drive motors $D_1$ and $D_2$, and, respectively, $N_1$ and $N_2$, which vary over time:

$$K_{Ni} = \frac{N_{1i}}{N_{2i}}. \quad (6)$$

Fig. 3 shows the behaviour of the changing capacities $N_1$ and $N_2$ developed by the drive motors of the belt conveyor 2LU120V. The characteristic curves reveal a significant effect of the transported load weight on the type of loading the drive motors. When the weight of the load transported by the conveyor is equal to W=70 tonnes, the conveyor drive motors are loaded uniformly, with $K_N$=1. When the weight of the load transported by the conveyor is W<70 tonnes, the drive motor $D_2$ is loaded more than $D_1$, and when W>70 tonnes, it is less loaded than the motor $D_1$. To quantify the unevenness, there is a mutual positioning of the capacity values of $N_1$ and $N_2$ of the drive motors depending on the transported load weight (Fig. 4), and the point cloud and the graph show a linear regression dependence of the capacity ratio of the drive motors $K_N$ depending on the relative conveyor loading (Fig. 5). The relative loading of the conveyor $W/W_{max} = 1$ corresponds to the full load of the drawbar element of the machine along the length of the transportation and the receiving capacity, where the value of $W_{max} = 126$ m indicates the maximum possible transportable load weight by the conveyor 2LU120V functioning in representative mine conditions along the length and in terms of the receiving capacity.

The following linear regression equations were obtained according to the results of the statistical processing of the dependencies of the low frequency component of the capacity developed by the drive motors $D_1$ and $D_2$ and the factor of their capacity dependence on the weight of the load transported by the belt – $N_1(W)$, $N_2(W)$, and $K_N(W)$, respectively:

$$N_{ji} = N_{jxi} + \Delta N_{ji} \cdot W_i, \quad (7)$$

where $N_{jxi}$ is the capacity of the idle j-th motor, kW; $\Delta N_{ji}$ is the increment of the energy consumed by the j-th motor at increasing the weight of the belt load by 1 tonne:

$$N_1 = 63 + 0.79W, \text{ kW}; \quad (8)$$

$$N_2 = 91 + 0.37W, \text{ kW}; \quad (9)$$

and for the coefficient of the drive motors capacities ratio the regression equation is the following:

$$K_{Ni} = K_{Nxi} + \Delta K_N \cdot W_i, \quad (10)$$

where $K_{Nxi}$ is the ratio coefficient of the capacities of the drive motors in the conveyor idle running mode; $\Delta K_N$ is the increment of the ratio coefficient of the capacities of the drive motors at increasing the weight of the load on the belt by 1 tonne:

$$K_N = 0.73 + 0.95 \cdot 10^{-3} \cdot W. \quad (11)$$

The correlation coefficients for the above-considered $N_1(W)$, $N_2(W)$, and $K_N(W)$, respectively, correspond to the following values:

$$r_{N1,W} = 0.978;\ r_{N2,W} = 0.956;\ r_{KN,W} = 0.958.$$

This confirms the linear dependencies $N_1(W)$, $N_2(W)$, and $K_N(W)$, which are close to functional. The calculated and tabulated Fisher criteria for the regression dependencies $N_{1c}(W)$, $N_{2c}(W)$, and $K_N(W)$, respectively, for 60.6 thousand measurements are as follows:

$$F_{N1,W} = 0.77 < F_{0N1,W} = 1.0;$$

$$F_{N2,W} = 0.88 < F_{0N2,W} = 1.0;$$

$$F_{KN,W} = 0.78 < F_{0KN,W} = 1.0.$$

This confirms the adequacy of the regression models $N_1(W)$, $N_2(W)$, and $K_N(W)$.

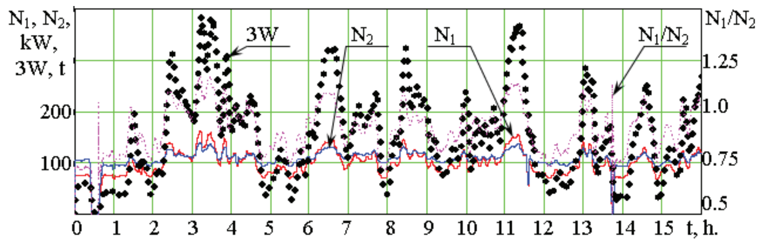


Fig. 3. Changes in the developed capacities of the drive motors $N_1$ (the thin red line) and $N_2$ (the thin blue line), the capacity ratio factor (the pink dots), and the weight of the transported load (the black marker) on the belt conveyor 2LU120V

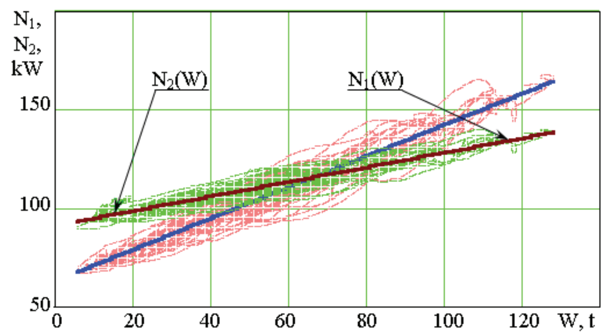


Fig. 4. The relative positions of the capacity readings of $N_1$ (the pink dots) and $N_2$ (the green dots) of the drive motors depending on the weight of the load transported by the belt, and the graphs of their regression equations (respectively, the blue and brown lines)

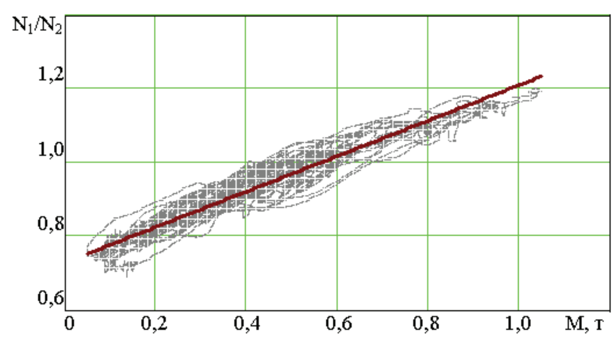


Fig. 5. The point cloud (the grey dots) and the graph (the brown line) characterizing a linear regression dependence of the capacity ratio factor of the drive motors on the relative loading of the conveyor

Thus, in real correlations, the ratio coefficient of the capacities of the drive motors $K_N$ varies from 0.69 to 1.21, and its value essentially depends on the weight of the load transported on the conveyor belt. When the values of the transported load weight on the conveyor belt do not exceed 70 tonnes, the capacity of the drive motor $D_1$ is smaller than of $D_2$ by 0...31 %. When the values of the transported load weight on the conveyor belt are more than 70 tonnes, the capacity of the drive motor $D_1$ is smaller than of $D_2$ by 0...21 %. Uneven loading of the drive motors adversely affects the resource of the machine. Therefore, this factor of an uneven load should be considered while creating a variable controlled drive and an intelligent system of managing a belt conveyor.

Much of the value of the capacity generated by the drive motors of a belt conveyor is determined by the distributed and lumped resistance forces taking place along the route of the conveyor. For extended conveyors, the biggest impact on the formation of the capacities of the drive motors is made by distributed resistance forces that are taken into account by the drag coefficient of the belt movement $\omega^{/}$. The actual value of resistance to the movement of the conveyor belt depends on the values of the operational parameters of the machine and can be determined by the experiment data. According to the methodology of calculating the proper parameters of a belt conveyor technology, the capacity of the machine that transports the load down at an angle of $\beta$ is determined as follows [2]:

$$N = gkv\eta^{-1}[(W + W_0 + W_p^{/} + W_p^{//})\omega^{/}\cos\beta - \\ - W\sin\beta],\ kW, \tag{12}$$

where $W_0 = 64.9$ tonnes is the weight of the conveyor belt; $W_r^{/} = 28.9$ tonnes is the weight of the rotating parts of the upper rollers of the conveyor; $W_r^{//} = 12.2$ tonnes is the weight of the rotating parts of the lower rollers of the conveyor; $k = 1.2$ is the factor that accounts for local resistance along the route of the belt conveyor; $\eta = 0.7...0.8$ is the efficiency factor of the electromechanical actuator.

By estimating the ratio $\omega^{/}$ at an idle running ($W = 0$), we get:

$$\omega^{/} = \frac{N_o\eta}{gkv(W_0 + W_p^{//} + W_p^{//})\cos\beta}. \tag{13}$$

For the experimental conditions, the drag coefficient in the belt movement will be $\omega^{/} = 0.05$, which is higher than the drag coefficient in the belt movement $\omega^{//} = 0.035$ that is recommended by common methods of the value calculation [2]:

$$\frac{\omega^{/} - \omega^{//}}{\omega^{/}}\cdot 100\ \% = \frac{0.05 - 0.035}{0.05}\cdot 100\ \% = 30\ \%,$$

which indicates that there is additional resistance to the belt movement occurring due to a longer operation life of the belt conveyor. One of the reasons for increasing the drag coefficient in the belt movement is jamming of the support rollers of the machine flight.

Thus, in the experimental conditions, the drag coefficient in the conveyor belt movement exceeds the calculated value by 30 %, which should also be taken into account in the traction and energy calculations for the machine.

For assessing the uneven load flow $Q(t)$ and its effect on the nature and magnitude of changes in the transported load weight $W(t)$ and on the capacities developed by the drive motors of the conveyor $N_1(t)$ and $N_2(t)$, the above-described parameters of the conveyor operation as random processes were evaluated by means of a correlational and spectral analysis.

The value of the normalized autocorrelation function for the time of a j-th step of a deviation $\tau_j = j\cdot\Delta t$ ($j = (0...l)$; $l$ is the maximum number of values of the autocorrelation function) was determined by the formula:

$$C_R(\tau_j) = \frac{\sum_{i=0}^{m-j}(R_i - \bar{R})(R_{i+j} - \bar{R})}{D_R(m-j)}, \tag{14}$$

where $R_i$ is an i-th value of a random process $R(t)$; $m$ is the number of values of the random process $R(t)$ during its implementation; $\bar{R}$, and $D_R$ are the expectation and variance of the random process $R(t)$.

The values of the normalized spectral density of the random process $R(t)$ are determined by the formula:

$$S_R(\omega_k) = \\ = \frac{\pi}{2}\sqrt{\left[\sum_{j=0}^{l} C_R(\tau_j)\cdot\cos(\omega_k\tau_j)\right]^2 + \left[\sum_{j=0}^{l} C_R(\tau_j)\cdot\sin(\omega_k\tau_j)\right]^2}, \tag{15}$$

where $\omega_k$ is the frequency of the harmonics of the random process $R(t)$.

The assumed minimum $\omega_{min}$ was a spectrum frequency determined by the length of a random process T, namely $\omega_{min} = 8\pi T^{-1}$; the assumed maximum $\omega_{max}$ was a multiple step sampling of readings on the capacity of the drive motors, from tensiometers and dynamometers: $\Delta t = 1s$, — $\omega_{max} = 20\pi\cdot(\Delta t)^{-1}$.

The magnitude of changes in the values of the range of $R(t)$ is estimated by the variation coefficient:

$$\nu_R = \frac{\sqrt{D_R}}{\bar{R}}. \tag{13}$$

For the correlational and spectral analysis as well as for assessing the value of the variation range of the parameters, a representative section was selected for implementing the net time of a continuous recording of the readings from tensiometers, dynamometers, and power sensors for the time duration of $T = 7.4\ h = 26.7\cdot 10^3$ s of continuous work of a belt conveyor with a non-controlled drive. This corresponds to the period during which the machine is switched on — between 16:57 of 25 May 2011 and 00:22 of 26 May 2011 of the calendar time.

The nature and magnitude of changes in the load flow and the transported load weight on the belt for the chosen area is shown in Fig. 6. The normalized autocorrelation function of the load flow $C_Q(\tau_j)$ and the transported load weight $C_W(\tau_j)$, as well as the corresponding spectral densities $S_Q(\omega_k)$ and $S_W(\omega_k)$, which were calculated according to the above-suggested formulas, are shown in Fig. 7.

The analysis of these dependencies (Fig. 6) reveals a big unevenness of the load flow $Q(t)$ and the weight of the transported load on the belt $W(t)$ in the absence of regulation of the transportation speed. The uneven load flow occurs due to the technological cycle of coal extraction in the clearing and preparatory faces and the combined machine performance. The coefficients of variation of the transported load flow and weight at a constant speed of the load transportation are close, and their values are, respectively, $k_{vQ} = 0.52$ and $k_{vW} = 0.48$. The smaller value of the variation coefficient of the transported load weight on the belt $k_{vW}$, in comparison with the coefficient of variation of the load flow $k_{vQ}$, is caused by smoothing high flow frequencies during loading the belt along the length of the conveyor ($t = 6$ min) while the transported load weight W(t) is formed therein. These frequencies are caused by unevenness of the feed rate produced by the cutters-loaders, the direction of their movement (in the bidirectional mode of extraction), and the work of the downhole and transportation equipment prior to the tests on the conveyor.

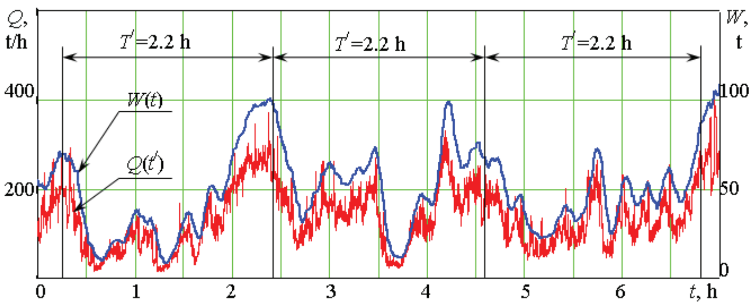


Fig. 6. Changes in the time of the load flow Q(t′), the red line, and the weight of the load transported on the belt W(t), the blue line, during the conveyor operation from 16:57 on 25 May 2011 till 00:22 on 26 May 2011

as the autocorrelation functions, are almost identical, which indicates that the distribution of the process dispersions is almost the same in the relevant frequencies.

Thus, the load flow of the mined bulk during intensive coal mining in two clearing and one preparatory faces is characterized by high non-uniformity (the coefficient of variation is $k_{vQ} = 0.52$), which largely determines the type and the uneven weight of the load on the belt (the coefficient of variation is $k_{vW} = 0.48$) at an unregulated speed of the conveyor. The uneven load flow occurs due to the technological cycle of coal extraction in the clearing and preparatory faces, the direction and the speed of the movement of combined machines (in a bidirectional mode of mining), and the test-preceding work of the downhole and transportation conveyors. The main variances of the load flow (75 %) and the transported load weight (85 %) coincide with low frequencies corresponding to the periods of $T_1 = 2$ h 8 min and $T_2 = 1$ h 3 min depending on the modes of extracting and transporting the mined bulk.

Fig. 8 shows the normalized autocorrelation functions of the capacities of the first $C_{N1}(\tau_j)$ and the second $C_{N2}(\tau_j)$ motors as well as the corresponding spectral densities $S_{N1}(\omega_k)$ and $S_{N2}(\omega_k)$.

A comparative analysis of the normalized autocorrelation functions of the load flow $C_Q(\tau_j)$ and the weight of the transported load on the belt $C_W(\tau_j)$ (Fig. 7, *a*) reveals that they are almost completely identical. These processes are characterized by the presence of random (fast fading) and periodic components. In this case, the RMS deviation in the processes $\sqrt{D_R}$ are: for the flow, $\sqrt{D_Q} = 72.7$ t/h; for the transported load weight, $\sqrt{D_W} = 23.7$ t. The periodic component, which is assessed by the autocorrelation functions that are recorded in the experiment, corresponds to the time interval $T = 2.2$ hours, which, in turn, corresponds to the average period of a maximum load flow as a result of a blending of the work cycles of two production faces and one preparatory face (Fig. 6).

The analysis of the normalized spectral densities of the load flow $S_Q(\omega_k)$ and the transported load weight $S_W(\omega_k)$ reveals that the main dispersion of the registered random processes are found mainly in the frequencies of $\omega_1 = 0.00083$ rad/s and $\omega_2 = 0.00166$ rad/s, which correspond to the oscillation periods of $T_1 = 2$ h 8 min and $T_2 = 1$ h 3 min (Fig. 7, *b*). The period $T_1$ is rendered as a result of registering the load flow in the experimental conditions and calculating the correlation function that corresponds to the random process; the reason for its occurrence is described above. The period $T_2$ corresponds to the technological cycle of intensive coal mining in the working face, and its numerical value will depend essentially on the mining technology adopted by an enterprise. The graphs (Fig. 7) show that the described frequencies account for more than 85 % of the variance of the transported load weight and more than 75 % of the load flow dispersion. The graphs of the normalized spectral densities of these processes at a constant speed of transportation, as well

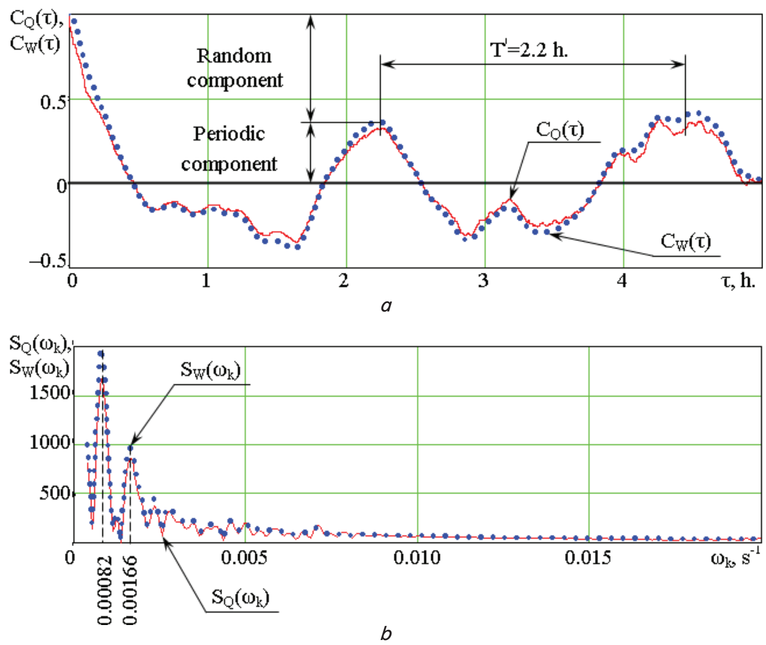


Fig. 7. The normalized autocorrelation functions of the load flow (the red line) and the weight of the transported load (the blue marker), as well as the corresponding spectral densities: *a* — the autocorrelation functions of the load flow $C_Q(\tau_j)$ and the transported load weight $C_W(\tau_j)$; *b* — the spectral densities of the load flow $S_Q(\omega_k)$ and the transported load weight $S_W(\omega_k)$

The analysis of these dependencies (Fig. 3) reveals a decrease in the unevenness of the capacities developed by the drive motors. The values of the capacity variation coefficients for the first and the second drive motors respectively constitute $k_{vN1} = 0.19$ and $k_{vN2} = 0.09$ due to the high capacity of the idle running of the belt and a redistribution of the total capacity developed by the machine between the drive motors. The coefficient of variation for the capacity of the second drive motor is 2.1 times lower than of the first drive motor. Consequently, the effect of an uneven distribution of the transported load weight W(t) on the capacity developed by the first drive motor, $N_1(t)$, is more substantial than the capacity developed by the second drive motor, $N_2(t)$.

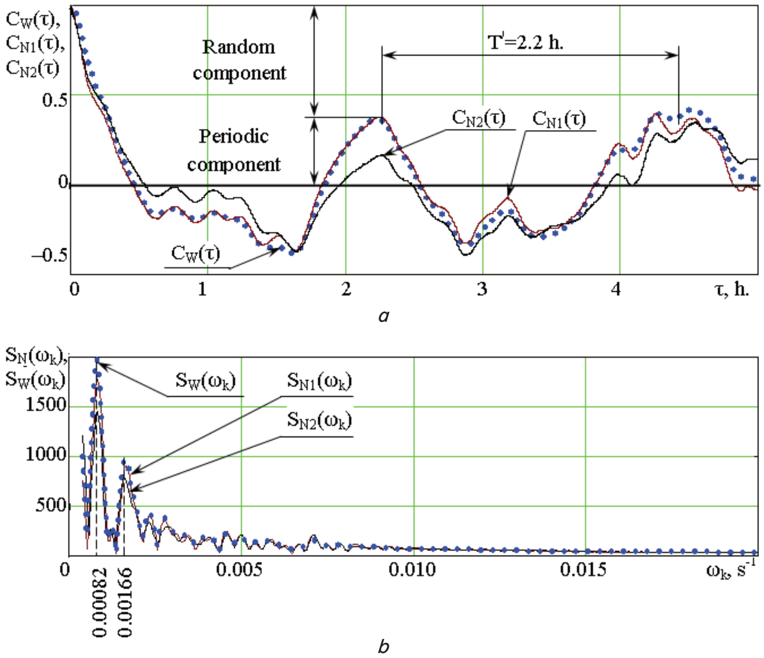


Fig. 8. The normalized autocorrelation functions of the transported load weight (the blue marker), the capacities developed by the drive motors, $N_1$ (the brown line) and $N_2$ (the black line), and the corresponding spectral densities: *a* — the autocorrelation functions of the capacities of the first $C_{N1}(\tau_j)$ and the second $C_{N2}(\tau_j)$ motors; *b* — the spectral densities of the capacities developed by the first $S_{N1}(\omega_k)$ and the second $S_{N2}(\omega_k)$ motors

The coefficients of variation for the capacities of the drive motors $N_1$ and $N_2$, according to (12), are determined by the formulas:

$$\nu_{N1} = \frac{\sqrt{D_{N1}}}{N_{1x} + \bar{N}_1}, \quad \nu_{N2} = \frac{\sqrt{D_{N2}}}{N_{2x} + \bar{N}_2}, \tag{16}$$

where $\sqrt{D_{N1}}$ and $\sqrt{D_{N2}}$ are the standard deviations of the capacities developed by the first and the second drive motors, respectively; $N_{1x}$ and $N_{2x}$ are the capacities of an idle running of the first and the second drive motors, respectively, derived from the regression equations (8) and (9): $N_{1x} = 63$ kW and $N_{2x} = 91$ kW; $\bar{N}_1$ and $\bar{N}_2$ are the average increments of the capacities generated by the motors during transporting the load by the conveyor. According to the experiment results for the given implementation area, $\bar{N}_1 = 40$ kW and $\bar{N}_2 = 20$ kW.

The RMS deviation in the capacities $N_1$ and $N_2$ developed by the motors respectively constitute $\sqrt{D_{N1}} = 20$ kW and $\sqrt{D_{N2}} = 10$ kW. Consequently, $\nu_{N1} = 20/(63+40) = 0.19$ and $\nu_{N1} = 10/(91+20) = 0.09$. Excluding the idle running capacities, the values of the coefficients of variation in terms of the increments of these capacities are about $\nu_1 \approx \nu_2 \approx 0.5$, which corresponds to the values of the coefficients of variation of the load flow and the transported load weight.

The correlational and spectral analysis of the capacities developed by the drive motors confirms an impact on them made by the dispersions of low-frequency components of random processes associated with the mineral extraction technology used by the mining enterprise. The graphs of the normalized autocorrelation functions (Fig. 8, *a*) and the spectral densities (Fig. 8, *b*) of the processes in question — respectively, $C_{N1}(\tau_j)$ and $C_{N2}(\tau_j)$ as well as $S_{N1}(\omega_k)$ and $S_{N2}(\omega_k)$ — are also almost identical. Besides, at a constant speed of the belt, there is an impact of the dispersions of these processes at the frequencies $\omega_1$ and $w_2$, corresponding to those in the graphs of the normalized autocorrelation functions as well as the spectral densities of the load flow Q(t) and the load weight transported on the belt W(t). These frequencies correspond to more than 80 % of the capacity variance of the drive $N_1$ and to more than 70 % of the capacity variance of the drive $N_2$. Therefore, while increasing the technical level of the belt conveyor for intensive coal mining, it is primarily necessary to optimize the mining technology of the enterprise. The effect of time on loading the conveyor to the capacities of the drive motors at a constant belt speed is not essential because the time of loading the conveyor (t = 6 min) is much shorter than the periods associated with the technological processes of mining at the enterprise in question, for they are measured in hours ($T_1 \approx 2.2$ h and $T_2 \approx 1$ h).

Thus, the correlational and spectral analysis of the capacities developed by the drive motors has revealed a significant effect of the character of changes in the load flow and the belt-transported load weight on the capacities developed by the drive motors. When the belt conveyor drive is unregulated, the unevenness of capacities of the first and the second drive motors (the variation coefficients are, respectively, $k_{vN1} = 0.19$ and $k_{vN2} = 0.09$) is less significant as compared with the unevenness of the load flow and the transported load weight due to the high capacity of the idle running of the drive motors of the tested conveyor. The influence of the uneven distribution of the transported load weight on the motor that is located in the place of the belt running off the drive is less substantial than on the motor that is located in the place of the belt running onto the drive of the conveyor. The main dispersion of the capacities of the first (85 %) and the second (75 %) drive motors, the same as the main dispersion of the load flow and the transported load weight on the belt, coincides with low frequencies corresponding to the periods of $T_1 = 2$ h 8 min and $T_2 = 1$ h 3 min, depending on the technologies of extracting and transporting the mined bulk.

Consequently, to improve the technical level of the transport machines for intensive coal mining in modern mines and to establish a constant load flow, it is advisable to create cutters-loaders with a constant productivity of extracting coal (rock). To maintain a steady weight of the load on the belt when one of the faces starts or stops working and the mined bulk comes to the assembled belt conveyor, it is advisable to regulate the speed of the conveyor belt along with the regulation of the performance of the main technological equipment. In addition, it is advisable to use other methods of balancing the load flow — for example, to use mechanized bunkers. A positive impact on energy consumption and the belt resource is made by reducing the amplitude of loading the electrical and mechanical parts of the belt conveyor.

Specific energy consumption for transporting 1 tonne of the mined bulk across a distance of 1 km on a conveyor belt will make [2]:

$$E(W_i)=\frac{N_i}{3.6vW_i}\ \text{kW}\cdot\text{h}/(\text{t}\cdot\text{km}). \tag{17}$$

The weight of the load on the belt $W_i$ corresponds to the average value of the load flow $Q_{av.i}$, which is equal to the following:

$$Q_{av.i}=\frac{3.6W_i v}{L}\ \text{t/h}. \tag{18}$$

Fig. 9 shows a dependence of the relative increase in energy consumption $C_e$ for transporting the load by a conveyor on the load factor along the length of the belt and in terms of its receiving (loading) capacity $C_l$.

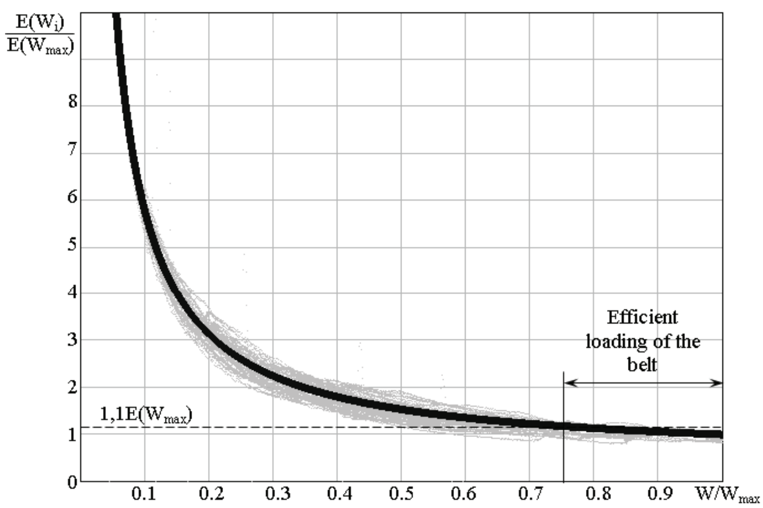


Fig. 9. The dependence of a relative increase in energy consumption for transporting the load on the factor of the belt loading along the length and in terms of the receiving capacity of the belt conveyor: the experiment data are in black dots, and there is a graph that corresponds to the formula (17)

The above-described factors are determined by the correlations:

$$C_l=\frac{W_i}{W_{max}}, \tag{19}$$

$$C_e=\frac{E(W_i)}{E(W_{max})}, \tag{20}$$

where $W_{max}$ is the weight of the load transported on the belt and corresponding to the maximum loading capacity of the conveyor; $E(W_{max})$ is energy consumption for transporting 1 tonne of the mined bulk across a distance of 1 km, corresponding to the weight of the load $W_{max}$; $E(W_i)$ is energy consumption for transporting 1 tonne of the mined bulk across a distance of 1 km, corresponding to the weight of the load $W_i$.

The analysis of the dependence of specific energy consumption for transporting the load by the belt conveyor reveals that when the value of the coefficient of loading the conveyor for its length and receiving capacity is $C_l = 0.75...1.0$, the ratio of the relative increase in energy consumption does not exceed $C_E = 1.1$, which means that the energy loss while transporting the load will not exceed 10 % of the optimal value of energy consumption. If the value of the conveyor loading factor is $C_l = 0.5$, the coefficient of the relative increase in energy consumption is $C_E = 1.5$; at $C_l = 0.25$, $C_E = 2.6$; at $C_l = 0.1$, $C_E = 7.75$. Consequently, at $C_l < 0.75$, it is expedient to regulate the speed of the conveyor belt in order to reduce energy consumption for transportation – if it is possible to reduce the speed according to the condition of the receiving capacity of the conveyor at a variable load flow.

## 6. Discussion of the experiment results

The main advantage of the conducted research is that it has resulted in determining specific factors in representative conditions of intensive coal mining (in two treatment faces and one preparatory face):

– the determining influence of the type and amount of the load flow on the uneven loading of the belt when the conveyor drive is unregulated;

– a significant effect of the uneven loading of the belt on the type and unevenness of the loading of the motors, which determine the conveyor resource, and energy consumption.

The drawback of this study is a large sampling interval (1 s), which does not allow the experiment to register the high-frequency component of loading the drive motors in stationary and transient modes of the belt conveyor operation.

The obtained data can be used:

– in a conceptual development of innovative structures and highly resource-efficient transport machines of a high technical level as well as mechatronic transport systems for intensive coal mining;

– in CAD systems of conveyor transport for mining enterprises with intensive mining of mineral resources.

Directions for further research include:

– conducting a complex of studies to establish the effect of the uneven load flow and load weight distribution along the conveyor belt on the dynamic loading and resource of the elements of its design;

– justification of the structure, parameters and algorithm of an adaptive control over the operation of the belt conveyor as a mechatronic object and the conveyor lines that contain devices for stabilizing the load flows;

– justification of the space and design parameters as well as optimization criteria and the development of the objective function to optimize a belt conveyor that has a variable speed drive and conveyor lines as mechatronic systems;

– development of CAD mathematical software, taking into account the patterns determined by experimental studies, including;

– adequate mathematical models of the workflow for intensive production of a functioning belt conveyor as a mechatronic object with an adaptive drive control system;

– a mathematical model of optimizing and justifying the structure and parameters of a controlled drive and an algorithm of an adaptive belt conveyor control system for the modern mining industry.

The solution of these tasks will help solve the problem of intensifying coal mining in terms of creating reliable and effective belt conveyors of a new technological level for the mining industry. These conveyor belts, along with the diagnostics and monitoring of the equipment without disconnecting from the circuit, will have optimized energy consumption for the transportation capacity and the resource of the component parts of conveyor lines that contain devices for stabilizing load flows within a mechatronic mining production system.

## 7. Conclusions

1. It has been experimentally determined that in conditions of intensive coal mining the load flow of the mined bulk from several faces and the consequently formed workload of the belt of the double-drive conveyor 2LU120V have a significant impact on the loading of the drive motors and energy consumption for transporting the load. The total capacity developed by a drive of a belt conveyor at an idle running (with the weight of the load on the conveyor belt being 2...3 % of the maximum possible load of 122 tonnes) is 150...170 kW; when the conveyor starts working, it amounts to 380 kW. In the mode of transporting the load, the capacities that are developed by each driving motor vary within the range of 70 kW and 180 kW, and their ratio depends essentially on the weight of the load transported by the conveyor. The ratio of the capacities of the conveyor drive motors, characterized by the dynamic loading and the defining resource of its elements, ranges from 0.69 to 1.21. When the values of the transported load weight on the conveyor belt does not exceed 70 tonnes, the capacity of the drive motor in the place of the belt running onto the drive is 0...31 % less than of the drive motor in the place of the belt running off the drive. When the values of the transported load weight on the conveyor belt exceed 70 tonnes, the capacity of the drive motor in the place of the belt running onto the drive is 0...21 % less than of the drive motor in the place of the belt running off the drive.

2. The load flow of the mined bulk during intensive extraction of coal in two clearing faces and one preparatory face is characterized by high non-uniformity (the coefficient of variation is $v_Q = 0.52$), which largely determines the type and the uneven weight distribution of the load along the belt (the coefficient of variation is $v_W = 0.48$) at an unregulated speed of the conveyor. The uneven load flow occurs due to the technological cycle of coal extraction in the clearing and preparatory faces, the direction and speed of the movement of combined machines (in a bidirectional mode of mining), and the work of downhole and transporting conveyors preceding the tested conditions. The main variances of the load flow (75 %) and the weight of the transported load (85 %) coincide with low frequencies, which correspond to the periods of $T_1 = 2$ h 8 min and $T_2 = 1$ h 3 min and depend on the technologies of extracting and transporting the mined bulk. When the drive of the belt conveyor is unregulated, the unevenness of the capacities of the first and the second drive motors (the variation coefficients are, respectively, $v_{N1} = 0.19$ and $v_{N2} = 0.09$) is less significant as compared with the unevenness of the load flow and the transported weight of the load due to the high capacities of the idly running drive motors of the tested conveyor. The effect of the non-uniformity of the transported load weight on the capacity developed by the drive motor that is located in the place of the belt running off the drive is less significant than the capacity generated by the motor that is located in the place of the belt running onto the drive of the conveyor. The main dispersion of the capacity of the first (85 %) and the second (75 %) drive motors, the same as the main dispersion of the load flow and the transported load weight on the belt, coincides with low frequencies corresponding to the periods of $T_1 = 2$ h 8 min and $T_2 = 1$ h 3 min due to the technologies of mining and transporting the mined bulk. Energy losses in an idle mode depend on the mode duration and make up 160 kW·h/hour. The minimum value of energy consumption for transporting a load by a belt conveyor corresponds to its work at full loading of the belt along the length and depending on its receiving capacity; it is 0.34 kW·h/(t·km). A reduction of the value of the load factor along the length and depending on the receiving capacity leads to a hyperbolic increase in energy consumption for transportation. When the conveyor load factor is 0.75, energy consumption for transportation increases by 10 %; if it is 0.5, the increase is by 50 %; if it is 0.25, the increase is by 160 %; if it is 0.1, the increase is by 675 %.

3. The value of the drag coefficient of the conveyor belt movement in representative conditions of intensive extraction is 0.05, which is 30 % higher than the value recommended by common methods of calculation.

4. One of the ways of increasing the efficiency of belt conveyors to intensify coal mining is to maintain the conveyor belt loading along the length and up to the receiving capacity in a given range, ensuring a maximum reduction of energy consumption for transporting the mined bulk. This is achieved by uniformity of the loading on the belt along its length and up to its receiving capacity as well as by varying the speed of the conveyor drawbar organ in case of an uneven supply of the load. To improve the technical level of transport machines for intensive coal mining in modern mines with the aim of establishing a constant load flow, it is advisable to create cutters-loaders with a steady capacity of extracting coal (rock). To maintain a stable weight of the load on the belt, when one of the supplying faces starts or stops working, it is advisable to regulate the conveyor belt speed along with the regulation of the performance of the main technological equipment and to stabilize load flows by using equipment of the transport lines. The amplitude of loading the electrical and mechanical parts of the conveyor belt can be reduced as a result of the above-described activities to have a positive impact on energy consumption and the resource of the belt conveyor.

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