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Determination of the Operating Time and Residual Life of Self-propelled Mine Cars of Potassium Mines on the Basis of Integrated Monitoring Data

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Statistical data on the reliability of self-propelled mine cars (SPMC), operating in the potassium mines of the Verkhnekamskoye potassium and magnesium salts deposit are analyzed. Identified the main nodes that limit the resource SPMC. It has been proven that the most common failures of self-propelled cars are the failure of wheel hubs, bevel gears and traveling electric motors. The analysis of the system of maintenance and repair of mine self-propelled cars. It is indicated that the planning and preventive system of SPMC repairs is characterized by low efficiency and high material costs: car maintenance is often carried out upon the occurrence of a failure, which leads to prolonged downtime not only of a specific haul truck, but of the entire mining complex. A method for assessing the technical condition of the electromechanical part of a mine self-propelled car by the nature of power consumption is proposed. This method allows you to control the loading of the drives of the mine self-propelled car, as well as to assess the technical condition of the drives of the delivery machines in real time.

Upon expiration of the standard service life of a mine propelled car specified in the operational documentation, its further operation is prohibited and the car is subject to industrial safety expertise. As part of the examination, it is necessary to determine the operating time and calculate the service life of a mine self-propelled car outside the regulatory period. A method has been developed for determining the residual service life of mine car on the basis of instrumentation control data in the conditions of potash mines.

Key words: mine self-propelled car; technical condition; loading; drive unit; operating time; life time; crash

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Introduction. For the enterprises of the potassium industry, the urgent tasks are to increase the reliability of mine transport equipment, increase productivity and reduce the cost of operation, maintenance and repair of machines [8, 11]. The lack of scientifically based methods for estimating the operating time and residual life of mechanical transmission units of delivery vehicles, the low information content and the complexity of implementing the methods used to control the technical condition lead to an increase in the number of accidental failures, the elimination of which is accompanied by prolonged downtime of not only the specific transporting machine, but also equipment operating in conjunction with it. The performance of the entire mining complex depends on the stable operation of the self-propelled mine car (SPMC) as a technological unit, therefore it is necessary to ensure the efficient and uninterrupted operation of the SPMC.

Improving the operational reliability of self-propelled cars of potassium mines is possible through the development and implementation of on-board systems for continuous monitoring of operating parameters and the technical condition of SPMC as an element of the system of measures to maintain their readiness [10]. The basis of the operation of these onboard systems should include the analysis of the recorded data, means of warning about unacceptable development of events and emergency protection devices [6, 12, 15, 16].

Basic information about the reliability of self-propelled mine cars of potassium mines. At the enterprises of the Verkhnekamskoye potassium-magnesium salt deposit, self-propelled cars of type 10BC-15 and BC-30 (Fig. 1) produced by Rudgormash Management Company ltd. are used. Under the current chamber development system, the SPMC deposits are the main mode of transport of the rock mass from the heading and digging combine to local or long-haul vehicles. Mine-propelled cars are characterized by high performance and mobility, can be used to deliver waste rock in the conduct of filling operations.

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a *b*

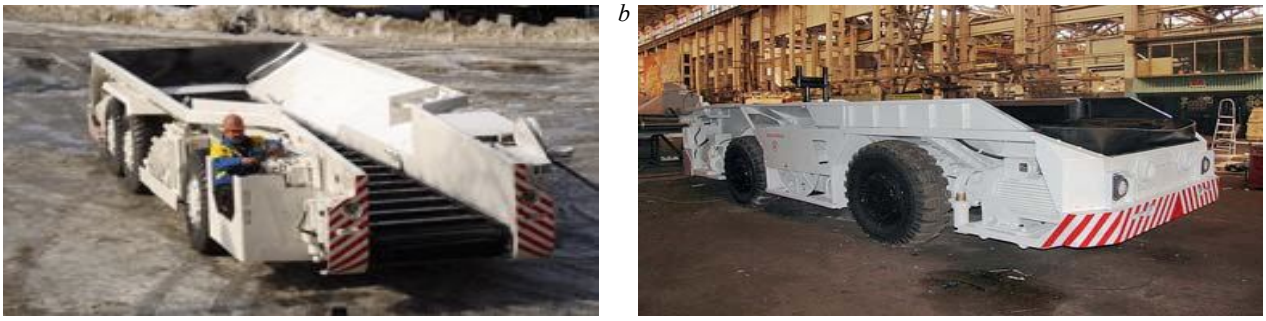


Fig.1. Self-propelled mine cars: *a* – 10BC-15; *b* – BC-30

However, the basic models of these cars were designed 30-40 years ago. The increasing productivity of modern excavation machines leads to the intensification of the operation of self-propelled cars, which leads to an increase in the flow of failures. Analysis of the causes of accidental failures allows us to conclude that most of the self-propelled mine cars fail parts and elements of the chassis, traction motors, electrical equipment (Table 1).

Таблица 1

Causes of accidental failures of self-propelled mine cars

Crashed part	Share of total crashes, %		
	5BC-15M	10BC-15	BC-30
Drive wheel hub	15.6	18.2	31.9
Traction motor	11.5	16.9	15.1
Conveyor and oil station electric motor	2.6	11.4	7.9
Angular (conical) gearbox	2.8	4.9	10.5
Gearbox of the conveyor and oil station	6.5	2.8	8.5
Magnetic control station	17.0	13.2	6.8
Power cable	8.1	11.3	4.2
Conveyor chain	13.0	0.9	1.4
Bridge beams	4.3	5.8	3.4
Brake system	4.5	3.8	1.2
Cable pick up system	6.2	5.7	2.6
Steering	2.2	1.9	2.4
Wheel planetary gearbox	–	–	3.4

The greatest proportion of the total number of crashes is the destruction of the wheel hubs, which is caused by the impact on the wheels and the undercarriage of heavy stress, significant loads, especially when performing shunting operations, acceleration and braking. In self-propelled cars BC-30 (load capacity 30 t), hub failures amount to one third of the total number of crash failures of mine self-propelled cars.

SPMC traction electric motors are characterized by low reliability. According to the operating organizations, the operating time of traction motors of BC-30 cars is from six months to a year. The main causes of failure of traction motors are wiring bands and winding breakdowns, which is caused by increased heating [13]. The cause of crash failures of conical (angular) gearboxes used in SPMC stroke drives is the destruction of the drive and driven gears. According to information received from service personnel, bevel gearboxes require complex and constant adjustment work during installation and operation [8, 14].

An acute problem arising in the operation of self-propelled cars such as BC-30 is the failure of tires and wheels. In the BC-30 car, which is fully loaded with potash ore, the load on the wheel is one and a half times greater than that of the 10BC-15 car. Three axles of the self-propelled car BC-30 and an independent drive for each drive wheel cause an uneven distribution of torques between the sides, which determines the breaking of kinematics at the gate, slipping of tires, increase of dynamic loads on tires and elements of drive drives.

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Wheels and tires SPMC fail for the following reasons: the appearance of a «hernia» on the side surfaces of the tire; tire carcass break; cracks on the sidewall and in the area of «blocks»; injuries received during operation – cuts, gusts, punctures; cracks and deformations of rims of diskless wheels, locking and side rings [9]. Tire replacement due to tread wear is practically non-existent. The nature of the damage suggests that the wheels work under loads close to the limit. During the shuttle scheme the tires of cars of increased capacity of the BC-30 form a track on the road, which is due to the tread parameters of the tires that are not designed for operation in a potash mine [9].

Regulatory documents of the manufacturer and operating enterprises established the technical service of SPMC using the planned-preventive system of organization of repair works, which implies every work shift, daily and monthly maintenance. The scope of current repairs of a self-propelled car is determined on the basis of an analysis of the revealed deviations from the standard parameters given in the operation manual. Repair of the self-propelled car is carried out in the period and time frame for repair of the heading and shearer. In fact, the maintenance and repair of mine cars are carried out on the basis of the analysis of information obtained in the course of diagnosis using organoleptic methods, and in the event of a failure.

The lack of on-board monitoring systems complicates the assessment of the operational load on the nodes of the self-propelled car, which makes it difficult to determine the size of the operating time and calculate the residual life of the mining vehicle, does not allow for timely repair actions aimed at preventing accidental failures.

Evaluation of the loading and technical condition of SPMC according to the instrument control. The most promising way to control the technical condition and operating parameters of transporting vehicles is to analyze the size and nature of the loads acting on the incoming water of self-propelled cars. The values of the instantaneous loads of the drives are determined by measuring the voltages, currents and powers consumed by the SPMC electric motors. The values and nature of changes in the energy parameters of drive engines are the most reliable and accessible primary information for further diagnosis [1, 3, 4].

Employees of the Perm National Research Polytechnic University developed a program-recording complex «Vatur» (Fig.2) [2].

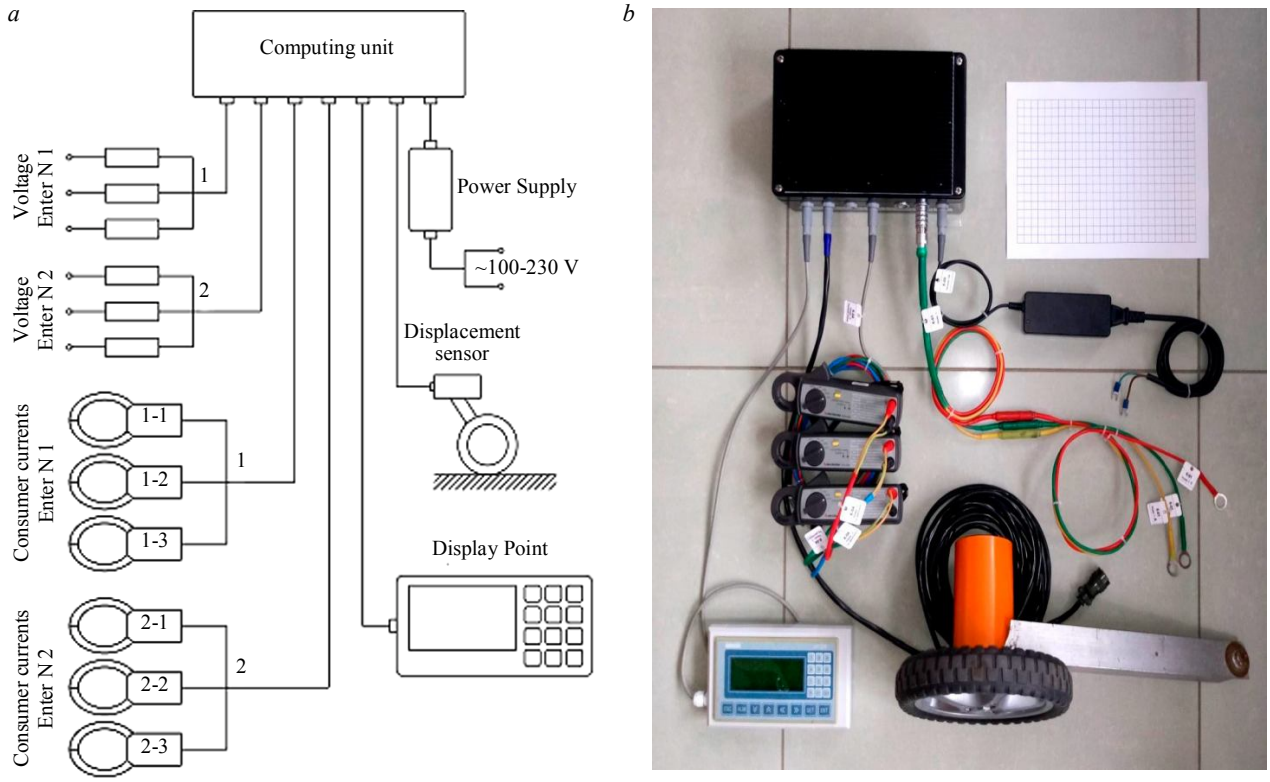


Fig.2. Program-recording complex «Vatur»: *a* – block diagram; *b* – general view

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The «Vatur» complex is located inside the SPMC magnetic station. The complex includes a processor unit, a power supply and switching unit, current and voltage sensors. Current sensors are current clamp-on pliers, by means of which the conversion of the input current into an output voltage is provided in a ratio of 1 A: 1 mV. The voltage sensor converts the input voltage up to 1000 V to the output voltage in a ratio of 1 V: 3 mV. During the measurement process, the data is stored in the non-volatile memory of the complex.

«Vatur» registers the electrical parameters of the drive motors of the car through two inputs of voltage. Measurements are performed at a frequency of 10 kHz. The initial processing of instant values is performed by the instrument software during the experiment. Further visualization, processing and analysis of data are carried out with the help of specialized software «Vatur-off» on a personal computer.

Studies of the size and nature of changes in the loading of drives of self-propelled cars 10BC-15 using the «Vatur» software-recording complex were conducted at one of the mines of public company «Uralkali». The profile of the route of the cleaning chamber at the initial section (in the direction from the combine to the place of unloading) with a length of 87 m had an inclination angle of ±2°. On the rest of the camera, the angle of inclination was +4°. The length of the track is 102 m, the self-propelled car is fully loaded (15 tons). Before conducting research, the voltage was measured when the SPMC drives were disconnected (700 V).

At the time of the start of the 10BC-15 car (Fig.3), the voltage drops to 611 V, the starting power consumed by the two electric motors running is 276 kW. A short-term increase in power up to 179 kW and a voltage drop of up to 646 V are observed when switching motors to a second speed. Thus, the site of acceleration SPMC characterized by the presence of excessive loads of traction motors. When switching the drive to the second speed, the peak load is less in amplitude than when the car is driven off, but longer. The part of the movement of the self-propelled car (*CD*) at the second speed is characterized by the nominal mode of operation of the drives and the absence of excessive loads. In the final section of the route (*DE*), the operator of the self-propelled car switches the propulsion engines to the first speed for a comfortable and safe approach to the ore-landing well.

At the beginning of the unloading of the 10BC-15 car (Fig.4), there is a short-term increase in the power of the conveyor motor to 127 kW (fourfold overload). As the body of the self-propelled car unloads, the value of active power decreases. SPMC full unloading takes 55 seconds. Thus, at the beginning of the unloading of the ore, the electric motor of the conveyor and the oil station SPMC is overloaded by 8-10 kW (about 30 %).

Spectral analysis of active power signals obtained by means of the measuring software-recording complex «Vatur» allows detecting frequency components from 0 to 25 Hz, which characterize oscillations of the kinematic chain «wheel – gearbox – running motor» (Fig.5).

Defects in the mechanical transmissions of SPMC cause the occurrence of variable loads, which causes the appearance of new spectral components. Periodic measurement in the power spectrum of the values characterizing specific defects in the mechanical transmission and the driving electric motor allows to evaluate the technical condition of the drive of the delivery machine and, if necessary, carry out repair actions aimed at preventing crashes. In transmissions of SPMC travel drives, by the nature of the change in the power signal, malfunctions of gears, distortions of the driven shafts and their bearings of rotation, gears on the shaft, misalignment of the driven shafts lined up in one line can be diagnosed [5]. In asynchronous electric motors, defects in the electric part of the rotor are diagnosed, including breaks in the rotor winding and the closure of the core plates; the electrical part of the stator, including breaks and electrical asymmetry of the power winding, the circuit plates of the core; static and rotating eccentricities; bearing defects leading to changes in air gap.

Evaluation of SPMC operating time according to instrument control data. Mine self-propelled car as a technical device used at a hazardous production facility is subject to industrial safety expertise upon expiration of the standard service life. As part of an industrial safety review, it

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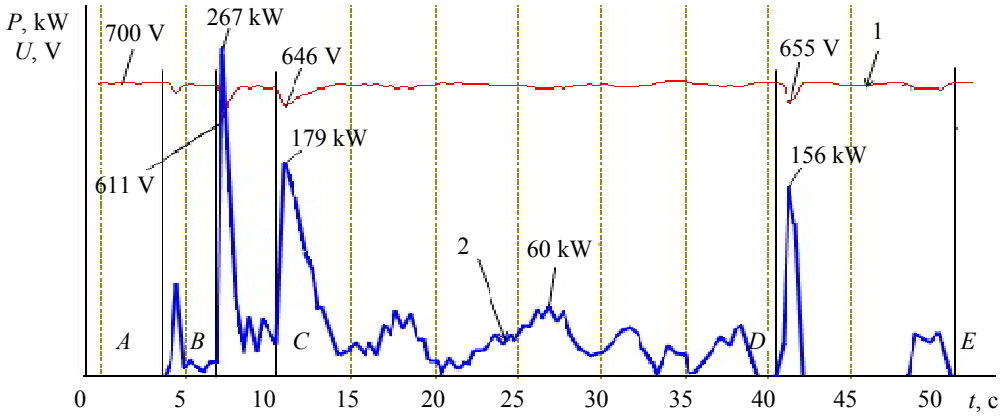


Fig.3. Graphs of changes in the energy parameters of drive motors loaded car 10BC-15

1 – voltage graph; 2 – graph of the sum of the active powers of the car traction motors; *AB* – start of the electric motors; *BC* – movement of SPMC at the first speed; *CD* – uniform movement of SPMC at the second speed; *DE* – car access to first speed ore passes

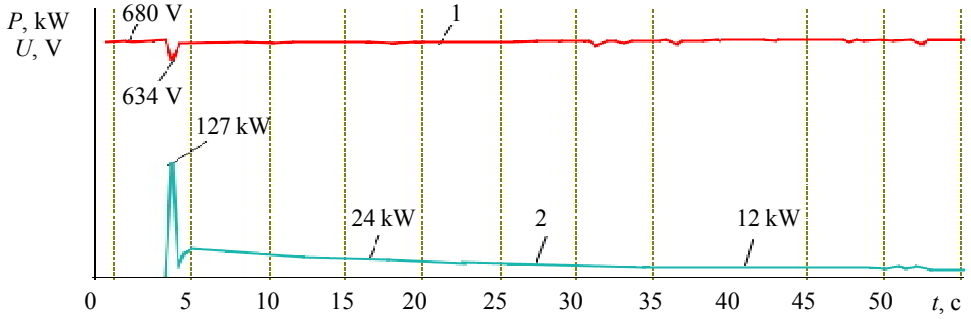


Fig.4. Graph of changes in the energy parameters of the conveyor motor and oil station when unloading the car 10DC-15

1 – voltage graph; 2 – plot of three-phase active power

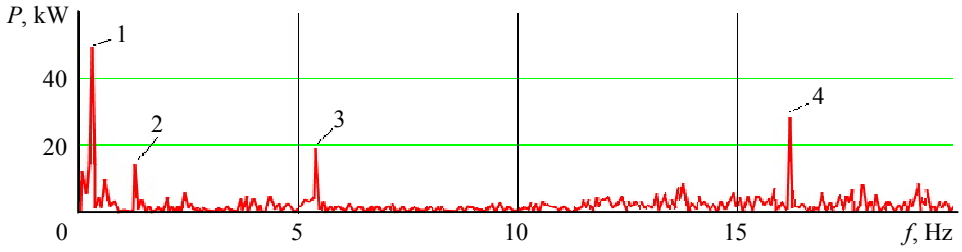


Fig.5. Spectrum of the active power signal of the mine car 10BC-15 driving motor

1 – wheel rotational frequency (f = 0,4 Hz); 2 – rotation frequency of the planetary gear reducer satellites (f = 0.95 Hz); 3 – the rotational speed of the driven gear bevel gear (f = 5.4 Hz);4 – the frequency of rotation of the drive motor shaft (f = 16.1 Hz)

is necessary to determine the operating time of a self-propelled car and the residual service life – a calendar period for which the mining vehicle can be extended (GOST 27.002–2015. Reliability in engineering: Basic concepts. Terms and definitions. M.: Standardinform, 2016, p. 28; Federal norms and rules in the field of industrial safety «Safety rules for mining and processing of solid minerals» (approved by order of the Federal Environmental Protection Service to whom, to technological and atomic supervision dated December 11, 2013 No. 599; registered in the Ministry of Justice of Russia on June 2, 2014, reg. No. 32935), 2013, p. 108).

It is known that gradual and sudden equipment failures caused by wear, deformation and breakdowns of parts can be described from a single energy point of view [1, 5, 6]. Studies of fatigue failure of metals show that the material of the part is destroyed when the critical value of internal energy is reached. Consequently, each element of the SPMC is characterized by a given energy op-

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erating time, which can be quantified, knowing the standard service life and the operating parameters of the self-propelled car.

Estimated operating time SPMC is determined by the formula

$$A_{\text{p}} = \frac{JU\eta T_{\text{n}} k_{\text{ws}} \cdot 24 \cdot 365}{1000 k_{\text{nu}}},$$

where A_{o} – estimated operating time, kWh; J – nominal current, A; U – supply voltage, V; η – efficiency of the SPMC electric motor; T_{n} – standard service life of a self-propelled car, appointed by the manufacturer, years; k_{ws} – the coefficient of work shift use of the machine, taking into account the implementation of operations not related to the main work on loading and transportation, is taken k_{ws} = 0.7 [7]; k_{nu} – coefficient of non-uniformity of cargo traffic, for calculating a self-propelled car, is taken to correspond to the greatest non-uniformity and equal to two [7].

The actual operating time of the SPMC stroke drive is determined by an electricity meter or by continuous recording of the active power of the motor of the controlled stroke drive over the calculation period from the start of operation to the actual monitoring time T_{a}:

$$A_{\text{a}} = \int_0^{T_{\text{ф}}} P(t)dt,$$

where A_{a} – the actual work performed by the drive stroke SPMC, kWh; $P(t)$ – active power consumed by the electric motor of the car, taking into account losses in the engine, kW.

The residual operating time of the self-propelled car is calculated by the formula

$$\Delta A = A_{\text{o}} - A_{\text{a}}.$$

When calculating the designated life time of SPMC, it is necessary to take into account that the aggressive mine atmosphere, slack, dust have a negative impact on the components and mechanisms of the mining and transport machinery, subjecting them to clogging, corrosion and, as a result, failure.

An indispensable, basic element of the SPMC is the body as supporting metalwork, which is experiencing heavy loads, but its repair is not provided for by the regulatory technical documentation of the manufacturer and operating company. Body of SPMC does not collapse in an emergency, and wear out gradually.

The car body (at the bottom of the scraper conveyor) is subject to corrosive, fatigue and abrasive wear due to the weight and abrasive impact of the rock mass. The specified wear leads to a loss of metal thickness, which can be controlled undermine conditions with the help of specialized equipment. The residual thickness of the metal body we estimate the degree of wear:

$$k_{\text{wear}} = \frac{l_{\text{res}} - l_{\text{max}}}{l_{\text{ini}} - l_{\text{max}}},$$

где k_{wear} – wear rate, which shows how many times the service life of SPMC is reduced with corresponding wear of the main element (body) of the car; l_{max} – maximum permissible thickness of the bottom of the body, mm; l_{res} – residual thickness of the bottom of the body, mm; l_{ini} – initial thickness of the bottom of the body, mm.

Determination of residual thickness l_{res} of th bottom of the body of the self-propelled car is carried out according to the instrument control – ultrasonic thickness gauging. Abrasive wear of the SPMC body occurs unevenly: the greatest metal losses are recorded at the place of ore loading in SPMC, the minimum wear – in the area of unloading (Table 2). Diagram of the body of the self-propelled car with measurement points is shown in Fig.6.

Table 2

The results of thickness gauging the bottom of a self-propelled car BC-30

Bottom section number	Measurement Point Number	Measured values l_{res}, mm
1	1.1	6.4
	1.2	7.0
	1.3	6.7
2	2.1	7.6
	2.2	7.0
	2.3	7.0
3	3.1	8.4
	3.2	8.1
	3.3	7.6
4	3.1	9.5
	3.2	9.6
	3.3	9.6

Note. Initial thickness l_{ini} = 10 mm.

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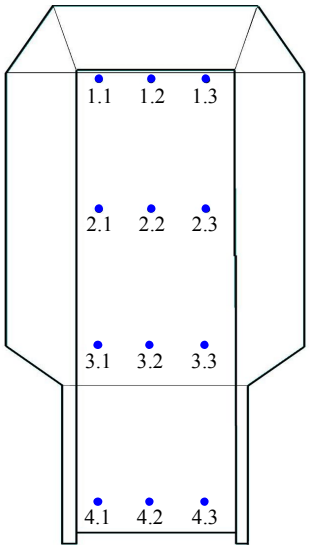


Fig.6. Scheme of a self-propelled car BC-30 body with measurement points bottom thickness

To calculate the assigned service life, the minimum residual thickness of the car body bottom l_{res}. The maximum allowable thickness of the bottom of the body l_{max} is determined by the results of strength calculations.

Residual life of a self-propelled car $T_{res.l}$ calculated based on the actual technical condition of the base element (body) and the life time of the SPMC at the time of the calculation:

$$T_{res.1} = \frac{\Delta A}{A_a / T_a} k_{wear},$$

where T_a – the actual service life of the self-propelled car at the time of the calculation, years.

Value A_a/T_a characterizes the average annual actual operating time of SMPC in kilowatt-hours. The ratio of the residual operating time of a self-propelled car to the average annual allows to determine the residual life of the mining vehicle, adjusted for the wear of the base element.

Conclusion. Continuous recording of the power consumed by the electric motors of the self-propelled car allows you to monitor the operational load of the nodes and drive elements of the delivery machine, as well as to assess its technical condition.

The proposed approach for determining the designated life time of SMPC allows you to:

• objectively evaluate the operating time of a self-propelled car in actual operating conditions;

• on the basis of instrument control, determine the degree of wear of the carriage elements that are not replaced during the operation;

• to fulfill the requirement of Rostekhnadzor during the examination of industrial safety of technical devices operated at hazardous production facilities.

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