PREDICTING RESIDUAL LIFE OF TORO-40D UNITS USING THE OIL SPECTRAL ANALYSIS METHOD

Bakytzhan Kyrgyzbay[1], Mergen Zhumanov[2], Yerbol Kaliyev[1], Nurbol Kamzanov[3], Nursat Baikenzhe[3], Rustem Kozbagarov[1,*]

[1]Mukhametzhan Tynyshbayev ALT University, Almaty, Republic of Kazakhstan
[2]Al Farabi Kazakh National University, Almaty, Republic of Kazakhstan
[3]Satbayev University, Almaty, Republic of Kazakhstan

*E-mail of corresponding author: ryctem_1968@mail.ru

Bakytzhan Kyrgyzbay 0009-0004-0317-7917,
Mergen Zhumanov 0009-0006-2977-6971,
Yerbol Kaliyev 0000-0002-1961-4809,
Nurbol Kamzanov 0000-0002-2420-8362,
Nursat Baikenzhe 0009-0000-0290-9056,
Rustem Kozbagarov 0000-0002-7258-0775

Resume

At the underground mines of Kazakhmys Corporation, where different types of highly productive self-propelled equipment with different types of pneumatic wheel drive are operated, there are significant downtime of technological equipment. As practice has shown, application of repair system with use of old methods and means, at operation of underground self-propelled equipment appeared to be ineffective. One of the main reasons of low efficiency of self-propelled machines operation is the absence of the system of continuous monitoring of technical condition of each machine and its aggregates with application of methods and means of diagnostics. To avoid failure, it is necessary to establish the predicted and residual resource at a certain operating time of the machine according to the diagnostics data. This paper outlines the results of research on predicting the residual life of machine units used in the conditions of the mine corporation “Kazakhmys”.

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1 Introduction

At present, the giant mines No. 55, 57, 65, 67 of Kazakhmys Corporation, where ore is extracted, are mines of a new type. Different types of highly productive self-propelled equipment with different types of drive on pneumatic wheels and caterpillars are operating in the faces of these mines. Most of the machines have diesel drive and articulated frame.

As practice has shown, the application of the repair system using old methods and means in the operation of underground self-propelled equipment proved to be ineffective. At the underground mines of Kazakhmys Corporation there are significant downtime of technological equipment. The duration of downtime ranges from 12% to 30% of the total time. From 20% to 30% of the total fleet of machines is constantly in repair, annual consumption of spare parts is from 15% to 20%, and materials - from 8 to 10% of the total costs of machinery and equipment; the number of repairmen is from 20 to 25% of the total number of underground workers [1-5].

One of the main reasons for low efficiency of self-propelled machines operation is the lack of a system of constant control of technical condition of each machine and its units with the use of diagnostic methods and means. Due to the fact that the value of working life before failure of the machine (unit) fluctuates within certain limits, there is a probability of failure during this period. To avoid failure, it is necessary to determine the predicted and residual resource at a certain operating time of the machine (unit) according to diagnostics data [6-8]. According to these data the terms of removal of aggregates or stopping the machine for repair are planned. This avoids emergency repairs and increases uptime of machine operation. Thus, increasing the failure-free operation of each machine unit with the use of methods and means of diagnostics, increases the performance of the machine as a whole.

Related to that, the research works directed on

Figure 1 *TORO-40D dump truck*

increase of workability of the machine by increase of failure-free operation of its aggregates with application of modern methods and means of resource diagnostics are current.

The planetary wheel reducers were selected as an object of research in this work. this is explained by the fact that each machine has four of them, and at the mines of Zhezkazgan work 68 dump trucks TORO-40D (Figure 1) and loading and transporting machines TORO-501 - 20 units. In addition, parts and assemblies of these gearboxes operate under sharply dynamic loads and are often overloaded. They have a relatively low durability, which makes it possible to quickly collect statistical material for calculations of resource parameters, labor intensity and cost of repair actions necessary for the development of repair standards and operational schedules of wheel gearboxes repair.

2 Materials and methods

Research in the field of maintenance of machines and equipment in serviceable condition, by means of methods and means of diagnostics, is carried out in aviation, railway and automobile transportation, machine-building plants.

Such studies for mining machinery and equipment have not been carried out. The transfer of developments from the above industries to the mining industry is impossible due to special operating conditions and distinctive features of the design of these machines [4-5].

In this paper, are given the results of researchers' works on increase of serviceability of self-propelled diesel machines on pneumatic-wheeled way by means of application of methods and means of diagnostics of removable units and theory of management of stocks of turnover fund.

The object of research is a wheel reducer of dump trucks TORO-40D, as a typical representative of units with a common oil bath and a considerable (over 240 pieces) number of them on dump trucks and loaders. Numerous researchers' experience showsexperience shows that the introduction of diagnostics processes of machines and equipment is one of the most important means of increasing their serviceability. Timely prevention of failures leads to reduction of their number and, as a consequence, to reduction of machine downtime; their inter-repair resource is more fully utilized.

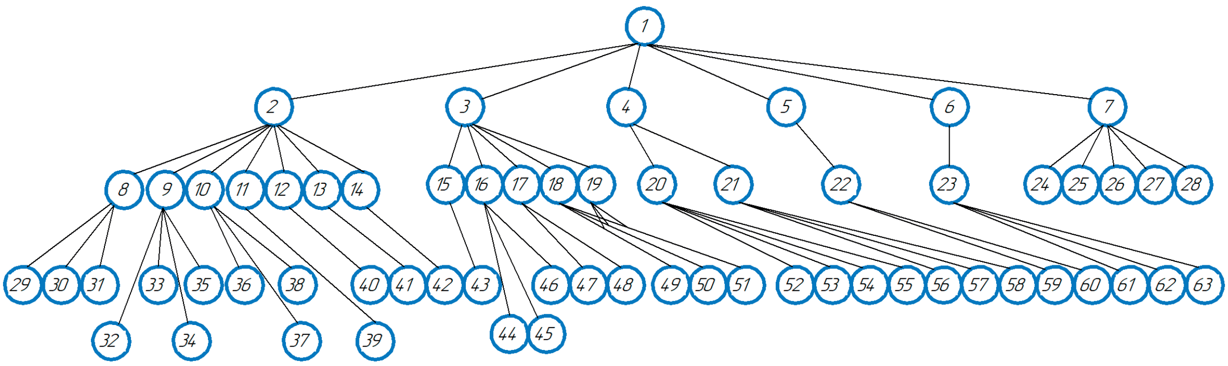
Technical diagnostics allows to increase productivity and efficiency of machine operation due to timely performance of adjustment, adjustment, repair and other preventive works.

It is known that the availability of complex systems deteriorates not only with the growth of failure rate, but with the increase in the duration of restoration of technical devices and, in particular, machines, as well. Considering that, the task of increasing the serviceability of machines as a result of improving the characteristics of recoverability: the time of searching for the failed element and the time of eliminating the failure is of great relevance. As it is known, modern repair systems are based on the aggregate repair method (ARM). The main condition for transfer of the main technological equipment to ARM is practical dismemberment of machines into interchangeable removable units, assembly units [7-9].

Machine parsing is aimed at developing such a nomenclature of removable elements, which would provide the most economical way of restoring the serviceability of machines in operating conditions.

Consequently, an optimal nomenclature of detachable units must be formulated for each machine (Figure 2). The main advantage of ARM is that the removable units are not repaired on the machine. Instead of defective ones, the machine is equipped with units from the revolving fund. Consequently, by improving the quality of manufacturing and repair of individual units, it is possible to increase the serviceability of the machine.

Structural parameters of each part working in



1 - road train; 2 - engine; 3 - transmission; 4 - control mechanism; 5 - frame; 6 - body control mechanism; 7 - electrical equipment; 8 - lubrication system; 9 - power system; 10 - cooling system; 11 - catalytic converter; 12 - cylinder-piston group; 13 - crank mechanism; 14 - gas distribution mechanism; 15 - gearbox; 16 - torque converter; 17 - cardan transmission; 18 - front axle; 19 - rear axle; 20 - steering control; 21 - brake system; 22 - halves articulation joint; 23 - hydraulic system of the body control; 24 - generator; 25 - starter; 26 - accumulator battery; 27 - voltage regulator; 28 - headlights; 29 - cleaning filters; 30 - hydraulic pump; 31 - oil radiator; 32 - high-pressure fuel pump; 33 - fuel pump; 34 - fuel filters cleaning; 35 - air cleaner; 36 - water pump; 37 - radiator; 38 - thermostat; 39 - catalytic cleaning unit; 40 - cylinder block; 41 - crankshaft, complete; 42 - camshaft, complete; 43 - frictions; 44 - pump wheel; 45 - turbine wheel; 46 - reactor; 47 - intermediate cardan shaft; 48 - drive axles cardan shaft; 49 - differential; 50 - wheel spur gear; 51 - wheel hub; 52 - hydraulic pump; 53 - steering cylinders; 54 - main steering distributor; 55 - "orbitrol" unit; 56 - hydraulic accumulators; 57 - brake valves; 58 - parking brake cylinders; 59 - front half-frame; 60 - rear half-frame; 61 - hydraulic pump; 62 - body lift cylinders; 63 - main distributor of the body hydraulic system

***Figure 2** Structural and functional diagram of the TORO-40D dump truck*

***Table 1** Chemical composition of TORO-40D dump truck wheel gearbox parts*

Ńo.	Name parts	Quantity	Average elemental content, %					
			C	Mn	Cr	Cu	Si	Ni
1	Solar gear	1	0.5	0.6	0.2	0.3	0.3	0.3
2	Idler gear	1	0.4	0.6	0.6	0.3	0.3	1.2
3.	Satellite	3	0.5	0.6	-	-	0.3	0.3
4	Satellite pin	3	0.4	0.6	0.9	0.3	0.3	0.3
5	Half-axle	1	0.5	0.6	0.2	0.3	0.3	0.3
6	Stocking	1	0.1	0.4	0.7	2.9	-	-
7	Driver	1	0.3	0.6	0.2	0.3	0.3	-
8	Half axle ring	1	0.4	0.6	0.5	0.3	0.3	0.3

a common oil bath are selected, when reaching the limit values of which the gearbox is removed for overhaul and a rational method of diagnostics.

The dominant method for diagnostics of units, the majority of parts and assembly units of which work in oil, is the spectral analysis of oil.

At AMR the degree of wear is established only for that part and mating parts of assembly units, at the limit wear of which the unit is removed for overhaul [10].

In experimental studies, the chemical composition of each part of the wheel reducer working in the same oil bath was carefully studied (Table 1).

When using the spectral analysis of oil, oil sampling is a very important operation. The standards for analysis were prepared based on the fresh engine oil used in the units of the TORO-40D dump truck (hydromechanical gearbox, axles, wheel reducers, etc.).

Oil samples were taken at critical times for the gearbox: after the running-in, refilling, oil change, at minimum values of technical life of parts working in a common bath before the gearbox removal [11-12]. The oil samples were analyzed in a special laboratory equipped with the MFS-7 unit and sample preparation units complete with an alternating current arc generator, tripod, semi-chromator and electronic recording unit, laboratory microanalytical type scales, etc.

3 Results and discussions

Implementation of diagnostics by spectral analysis of oil required a lot of preparatory work on measurements of worn surfaces of parts, processing of measurement data to obtain the wear from the total operating time $\delta = f(\sum R)$ and the mass of worn material of the part in the oil from the linear value of wear $m = F(\delta)$.

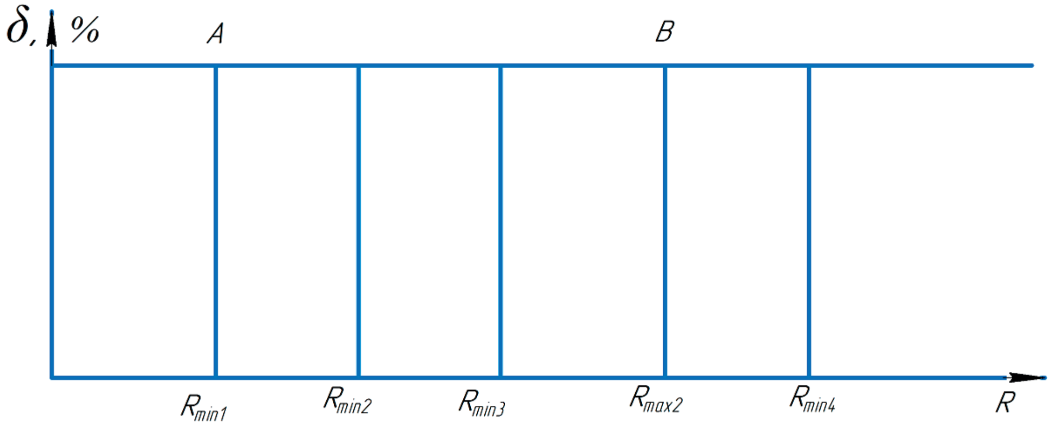


Figure 3 *Selection of parts to obtain service life parameters*

Table 2 *Average chemical composition of TORO-40D dump truck wheel gearbox parts*

No.	Name of parts	Quantity	Average elemental content, %					
			C	Mn	Cr	Cu	Si	Ni
1	Solar gear	1	0.5	0.6	0.2	0.3	0.3	0.3
2	Idler gear	1	0.4	0.6	0.6	0.3	0.3	1.2
3	Satellite	3	0.5	0.6	-	-	0.3	0.3
4	Satellite pin	3	0.4	0.6	0.9	0.3	0.3	0.3

To obtain these dependencies as quickly as possible, it was necessary to carry out a minimum number of measurements, i.e., to obtain data only for those parts for which the gearbox is removed for overhaul. In the work the probabilistic theory of resource distribution is accepted, in which each repair unit has minimum $(R_{\min})$, average $(\bar{R})$ and maximum $(R_{\max})$ values of resource, law and parameters of its distribution. The parts, because of which the gearbox is removed for overhaul, include parts that have a minimum value of the service life $R_{\min} \leq R_{\max}^{\min}$, where $R_{\max}^{\min}$ - the minimum value of the maximum service life. Figure 3 shows the graph of locations of $R_{\min i}$ and $R_{\max i}^{\min}$ for parts 1, 2, 3, 4 [13].

In the range from A $(R_{\min 1})$ to B $(R_{\min 2})$, there is a probability that parts 1, 2, 3 will fail and the gearbox will be removed for repair. When operating time $R_{\min 2}$ is reached, there is a 100% probability that part 2 will fail and the gearbox will be removed for repair. For parts with $R_{\min 1} \leq R_{\max 1}^{\min}$, instrumented measurements are used to calculate $\delta \leq \left(\sum R\right)$ and $\delta = F(m)$. In Figure 3 this applies to parts 1, 2, 3.

With the probabilistic theory of the service life value distribution, the wear limit may occur at different operating hours within the range of $R_{\min i}$ to $R_{\max i}$. In this case, for the selected group of gearbox parts it is necessary to set the alloying additives, the content of which in the oil will be used to judge the degree of wear of each part.

The most time-consuming task is the distribution of alloying additives in the gearbox crankcase among the parts depending on the degree of wear. In this case it is necessary to find the distinctive features for each part, by which it is established that it belongs to one or another of the components contained in the oil [14-15].

Table 2 shows the chemical composition of four parts of the gearbox, because of which the gearbox is removed for repair.

Based on Table 2, it can be stated that the amount of each additive is related to the number and amount of other additives. Using this relationship, a system of equations is developed. Mn is taken as the main alloying material, as it is contained in the materials of parts in greater values and equal quantities. For simplicity of calculation the equations are made for four components (Mn, Cr, Ni, Cu) and their masses are equated to the equivalent of Mn.

$$\sum Mn_j = Mn_1 + Mn_2 + Mn_3 + Mn_4\,, \tag{1}$$

where Mn_j, Mn_1, Mn_2, Mn_3, Mn_4 - amount of manganese in oil due to wear of parts 1, 2, 3, 4, g, respectively.

$$\sum Mi_j = Mi_1 + Mi_2 + Mi_3 + Mi_4\,, \tag{2}$$

where $\sum Mi_j$ - is the total mass of nickel contained in the gearbox crankcase at the time of sampling, g; Mi_1, Mi_2, Mi_3, Mi_4 - amount of nickel in oil due to wear of parts 1, 2, 3, 4, g, respectively.

Next, Mi is replaced by the equivalent Mn. According to Table 2, part 1 has 2 times more content than Mn, parts 3 and 4 have 2 times less content than Mn. Then, Equation (2) takes the following form

$$\sum N_1 = 0.5Mn_1 + 2Mn_2 + 0.5Mn_3 + 0.5Mn_4\,. \tag{3}$$

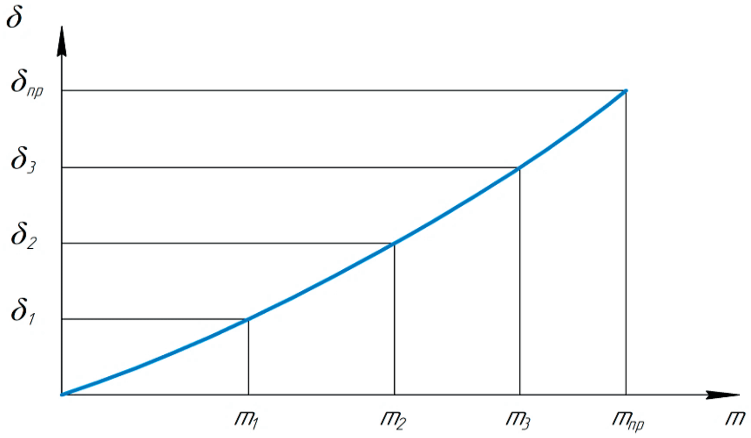


Figure 4 *Dependence of the wear rate δ on the worn metal weight m*

In the same way the equations for ΣCr and ΣCu are formed:

$$\sum Cr = 0.33Mn_1 + 2Mn_2 + 1.5Mn_4\,, \tag{4}$$

$$\sum Cu = 0.5Mn_1 + 0.5Mn_2 + 0.5Mn_4\,. \tag{5}$$

Spectral analysis data: ΣMn=240g; ΣNi=140g; ΣCr=80g; ΣCu=80g. From Equation (3) one finds $Mn_1 = 2\sum N_i - 4Mn_2 - Mn_3 - Mn_4$. From Equation (1) one obtains:

$$Mn_2 = \frac{2\sum Ni - \sum Mn}{3} = 13\text{g}\,. \tag{6}$$

In the same way is found ΣMn_1=132g; ΣMn_3=79g; ΣMn_4=16g. Using this data and the dependence $\delta = F(m)$ one can determine the amount of wear δ of each part after the next diagnostics.

All the instrumental measurements were carried out in the mining equipment plant (MEP) when disassembling the gearbox for repair and during the defective parts inspection. Measurement of linear dimensions of worn surfaces is carried out using the technological charts developed by the authors of the work. Measurement of the mass of the worn material m is carried out mainly by weighing the examined part. The mass of the worn material of the part mi; was found by the formula $m_i = m_H - m_B$, - then where m_H - the mass of a new part, taken from the working drawings; m_H - the weighed mass of the same part. Measurement data are processed and dependences $\delta = F(m), \delta = F(R)$ for each of 8 parts are obtained (Figure 4).

The wear limit $\delta_{\max}$ was taken from the manufacturer's data. According to $\delta_{\max}$ and the value of wear δ at operating time R, obtained by diagnostics, the predicted service life was found by the formula

$$R_{for} = R \cdot \sqrt[n]{\frac{\delta_{\max}}{\delta}}\text{, machine hours,} \tag{7}$$

where R - the operating time for the measurement period; n - coefficient, the value of which depends on the type of depreciation, is given in reference books.

On the example of satellites, the dependences of δ on alloying additives $\delta = f(m_{Cr}), \delta = f(m_{Cu}), \delta = f(m_{Ni})$ etc. were obtained. The sums $\sum m_{Cr}, \sum m_{Ni}, \sum m_{Mn}$ etc. were found for each operating time and at known values of wear.

$$\begin{aligned} &\sum m_{Cr} = m_{Cr1} + m_{Cr2} + \dots + m_{Crn};\\ &\sum m_{Ni} = m_{Ni1} + m_{Ni2} + \dots + m_{Nin};\\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\ &\sum m_{Mn} = m_{Mn1} + m_{Mn2} + \dots + m_{Mnn}; \end{aligned} \tag{8}$$

where $m_{Ni1}, \dots, m_{Nin}, m_{Cr1}, m_{Crn}, m_{Mn1}, \dots, m_{Mnn}$ - mass of nickel, chromium, manganese and other alloying additives at wear of $\delta_1, \delta_2, \delta_m$ from 1 to n-th parts, respectively.

Thus, for each operating time, it is calculated how much of each component should be in the oil from wear of all 8 parts. Using this data, the service life values, distribution laws and their parameters for each part of the wheel gearbox are established.

A method for determining the total mass of alloying additives that are contained in the drained and working crankcase oils has been proposed. This mass should correspond to the mass of worn material of the gearbox parts. The essence of the method is as follows [1-3]:

1. When the minimum oil level in the crankcase is reached, a sample is taken;
2. After taking the sample, top up to the maximum mark;
3. Oil refill volume is $V_y = V_{\max} - V_{\min}$, where $V_{\max}$, $V_{\min}$ - is the maximum and minimum crankcase oil volumes;
4. The total mass of components in the oil due to component wear and removed from the gearbox together with the leaked oil is calculated according to the formula:

$$\begin{aligned} &\sum m_{Cr} = m_{Cr1} + m_{Cr2} + \dots + m_{Crn};\\ &\sum m_{Mn} = m_{Mn1} + m_{Mn2} + \dots + m_{Mnn}\text{ etc.,} \end{aligned} \tag{9}$$

where $m_{Cr1}, m_{Cr2}, \dots, m_{Crn}$, $m_{Mn1}, m_{Mn2}, \dots, m_{Mnn}$ - mass of Cr, Mn and other components, respectively, removed

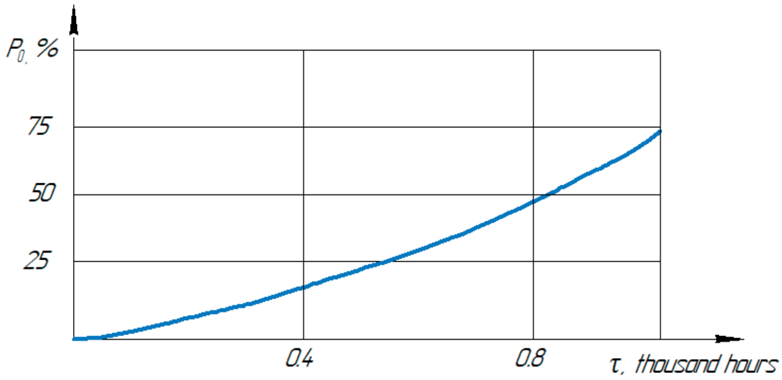


Figure 5 *Dependence of probability of emergency repair on the frequency of diagnostics*

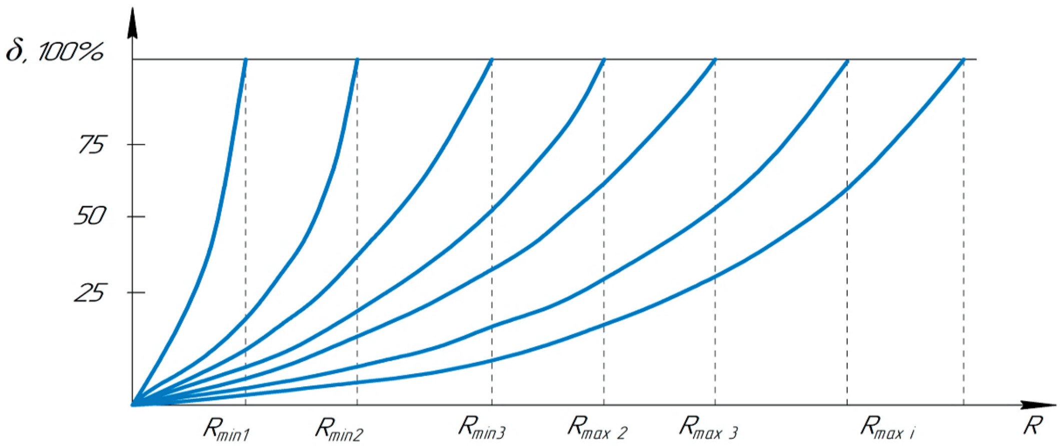


Figure 6 *Setting the optimal timing of diagnosis and the number of samples taken*

from the crankcase by the leaked oil and obtained after 1, 2 ... n topping up;

5. The total mass of each of the alloying additives that should be taken into account to obtain the dependencies $\delta = f(m_i)$, is found from the equation

$$\sum M_i = M_i^z + M_i^d + M_i^b , \tag{10}$$

where M_i^z, M_i^d - total mass of the i-th alloying additive removed from the crankcase during the replacement and leakage; M_i^b - mass of the i-th alloying additive at the last sampling from the oil running in the crankcase. Then, $\delta = f(\sum M_{Cr})$

The diagnostic intervals (τ) should be chosen so that the unit costs of diagnostics and repairs are minimized. The diagnostic intervals in general terms are determined by the formula

$$\tau = \mu \cdot R \text{, machine hours,} \tag{11}$$

where μ - optimality coefficient showing how many times the optimal periodicity is greater or smaller than the mean time between failures.

At exponential law of developments distribution, the optimality equation will have the form

$$e^{-\lambda\tau} - \lambda\tau - 1 - \frac{c_d}{d_d} = 0 , \tag{12}$$

where $\lambda = \frac{1}{R}$ - failure rate parameter.

Under the Weibull distribution law

$$\frac{\alpha\beta \cdot \tau^{\beta-1}}{e^{-\alpha \cdot \tau\beta}} \int e^{\alpha R^\beta} dR + \alpha\tau^\beta - \frac{C_{d.o}}{C_A} = 0 , \tag{13}$$

where α, β - distribution parameters.

Figure 5 shows the increase in the probability of emergency repair depending on the frequency of diagnostics for a certain mode of operation and operating conditions.

Oil samples are taken from the crankcase in the following cases: after the end of running-in of the product, each refilling and changing of oil, as well as to determine the degree of wear of individual parts working in an oil bath.

Periodicity of running-in, topping up and oil change is specified in the operating instructions. The sampling intervals and the number of samples to be taken can be optimized.

First of all, the gearbox parts and assemblies for which it is necessary to calculate the predicted service life R_{npi} are installed. For this purpose, the parts and assemblies with the shortest maximum life $R_{\max}^{\min}$ are selected (Figure 6).

On the graph (see Figure 6) δ, % - wear of parts; R - machine operating time in machine hour; $R_{\min 1}$, $R_{\min 2}$,

$R_{\min 3}$ - minimum values of service life of 1st, 2nd and 3rd parts, $R_{\max 1}, R_{\max 2}, R_{\max 3}$ - their maximum values, respectively.

When unit $R_{\max 2}$ has reached the end of its service life, it must be removed and sent for overhaul. The range from $R_{\min 1}$ to $R_{\max 2}$ includes values $R_{\min 1}$, $R_{\min 2}$, $R_{\min 3}$.

4 Conclusions

Increase of serviceability of self-propelled mining machines at the aggregate method of repair is achieved by increasing the failure-free operation of their aggregates by methods and means of resource diagnostics. This is achieved by reducing the costs of emergency repairs and losses from machine downtime in these repairs, thanks to the prevention of failures by methods and means of spectral analysis of oil, which allows to establish the predicted and remaining life of the unit before its removal.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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