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«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
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ANALYSIS OF TECHNICAL OPERATION OF CATERPILLAR ENGINEERING CORPORATION ENGINES IN INDUSTRY

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Abstract. The paper analyzes the technical operation of caterpillar engineering corporation engines in industry. Currently, new developments of Cat technology with mechanical power transmission are one of the advanced technologies for operation control in the segment of diesel-electric machines. A wide range of engines allows you to install, for example, the "C32" and "SAT3500" series on mining dump trucks. The engines meet Tier 3 standards for exhaust gas toxicity through the use of ACERT (Advanced Combustion Emissions Reduction Technology) technology. During operation, malfunctions and accidents of modern engines

occur, which lead to the shutdown and downtime of the equipment as a whole. The paper presents statistics of failures of Caterpillar engine components during 10 years of operation. visual and parametric control and defecation were performed to analyze the accident. The results of computer diagnostics were obtained, the authors, 20 hours earlier before the accident, made it possible to compare the same values taken immediately after the accident. To identify the causes of the accident of the C 32 automobile engine, types and methods of non-destructive testing were applied, taking into account the coefficient of operation in a quarry.

Keywords: car engine, diagnostics, load, engine defects, dump truck.

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ТАУ-КЕН ӨНЕРКӘСІБІНДЕГІ CATERPILLAR МАШИНА ЖАСАУ КОРПОРАЦИЯСЫНЫҢ ҚОЗҒАЛТҚЫШТАРЫНЫҢ ТЕХНИКАЛЫҚ ЖҰМЫСЫН ТАЛДАУ

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Аннотация. Мақалада caterpillar engineering corporation қозғалтқыштарының өнеркәсіптегі техникалық жұмысы талданады. Қазіргі уақытта

Механикалық қуат берумен Cat технологиясының жаңа әзірлемелері дизельдік-электрлік машиналар сегментіндегі жұмысты басқарудың озық технологияларының бірі болып табылады. Қозғалтқыштардың кең ассортименті, мысалы," C32 "және" SAT3500 " серияларын тау-кен самосвалдарына орнатуға мүмкіндік береді. Қозғалтқыштар ACERT (Жану Шығарындыларын Азайтудың Озық Технологиясы) технологиясын қолдану арқылы пайдаланылған газдардың уыттылығы бойынша 3-Деңгей стандарттарына сәйкес келеді. Жұмыс кезінде заманауи қозғалтқыштардың ақаулары мен апаттары орын алады, бұл тұтастай алғанда жабдықтың тоқтап қалуына әкеледі. Мақалада Шынжыр табанды қозғалтқыш компоненттерінің 10 жыл жұмыс істеген кездегі істен шығуы туралы статистика келтірілген. Апатты талдау үшін визуалды және параметрлік бақылау және дефекация жүргізілді. Компьютерлік диагностиканың нәтижелері алынды, авторлар апаттан 20 сағат бұрын апаттан кейін бірден алынған мәндерді салыстыруға мүмкіндік берді. С 32 автомобиль қозғалтқышының апатының себептерін анықтау үшін карьердегі жұмыс коэффициентін ескере отырып, бұзбайтын сынақтардың түрлері мен әдістері қолданылды.

Түйін сөздер: автомобиль қозғалтқышы, диагностика, жүктеме, қозғалтқыштың ақаулары, самосвал.

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АНАЛИЗ ТЕХНИЧЕСКОЙ ЭКСПЛУАТАЦИИ ДВИГАТЕЛЕЙ МАШИНОСТРОИТЕЛЬНОЙ КОРПОРАЦИИ CATERPILLAR В ГОРНОЙ ПРОМЫШЛЕННОСТИ

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Аннотация. В работе проведен анализ технической эксплуатации двигателей машиностроительной корпорации Caterpillar в промышленности. В настоящее время новые разработки техники Cat с механической силовой передачей являются одной из передовых технологий контроль эксплуатацией в сегменте дизель-электрических машин. Широкий модельный ряд автомобильных двигателей позволяет устанавливать, например, серии «С32» и «CAT3500» на карьерные самосвалы. Двигатели отвечают нормам Tier 3 по токсичности отработавших газов благодаря использованию технологии ACERT (Advanced Combustion Emissions Reduction Technology). В процессе эксплуатации происходят неисправности и аварии современных двигателей, которые приводят к остановке и простою оборудования в целом. В работе приведена статистика отказов элементов автомобильных двигателей самосвалов фирмы «Caterpillar» в течение 10 лет эксплуатации с учетом коэффициента работы в условиях карьера. Для анализа аварии были выполнены визуальный и параметрический контроль, дефектация. Получены результаты компьютерной диагностики, авторами, за 20 часов ранее перед аварией, позволили сравнить такие же значения, снятые сразу же после аварии. Для выявления причин аварии автомобильного двигателя марки С32 были применены виды и методы неразрушающего контроля с учетом коэффициента работы в условиях карьера.

Ключевые слова: автомобильный двигатель, диагностика, нагрузка, дефектации двигателя, карьерный самосвал.

Introduction. The large engineering corporation Caterpillar is introducing its internal combustion engines to the facilities of large open pit mining operations in Russia. The corporation introduced its first quarry off-road dump truck in 1962. Nowadays new developments of Cat machinery with mechanical power transmission are one of the advanced technologies of operation control in the segment of diesel-electric machines. A wide model range of engines for mining road transport allows to install, for example, series "C32" and "CAT3500" on mining dump trucks (Fig. 1). The engines meet the Tier 3 (Palyanitsina, et al., 2021; Korshak, et al., 2019; Korshak, et al., 2020) exhaust emission standards through the use of ACERT (Advanced Combustion Emissions Reduction Technology). It covers four engine systems for exhaust emission reduction and addresses the fuel system, the combustion process, the engine air intake system considering the application

factor of quarry operation and the implementation of an electronic monitoring and control system.

Rated power C32: 1007 kW at 2100 min^{-1} Engine type: V-12, 4-stroke diesel engine D/S: 145 / 162 mm Working volume: 32.1 litres Maximum torque range: 6166 N.m at 1400 min^{-1}	Rated power of CAT 3508: 746 kW at 1800 min^{-1} Engine type: V-8, 4-stroke diesel D/S: 170 / 190 mm Working volume: 34.5 litres Maximum torque range: 4263 N.m at 1450 min^{-1}	Rated power of CAT 3512: 1119 kW at 1800 min^{-1} Engine type: V-12, 4-stroke diesel engine D/S: 170 / 190 mm Working volume: 51.8 litres Maximum torque range: 6210 N.m at 1400 min^{-1}	Rated power of CAT 3516: 1492 kW at 1800 min^{-1} Engine type: V-16, 4-stroke diesel engine D/S: 170 / 190 mm Working volume: 69 litres Maximum torque range: 8391 N.m at 1400 min^{-1}

Fig. 1. Photos of Caterpillar career automobile engines

However, malfunctions and accidents of modern engines occur in the quarry environment during the operation considering the operation factor, resulting in stoppage and downtime of the overall equipment (Balovtsev, et al., 2024; Korshak, et al., 2023; Kusimova, et al., 2023; Pshenin, et al., 2023).

The purpose of the work is to develop a statistical, classified, generalised database on information of parameter values and collection and analysis of failures and malfunctions of automobile engines taking into account the coefficient of application of work in quarry conditions.

Materials and object of research. Analysis of literature sources shows that today a large number of works are devoted to the study of thermal parameters and operating conditions of mining power equipment and their elements (Gendler, et al., 2016; Gridina, et al., 2022; Klyuev, et al., 2024; Ligotsky, et al., 2024). In the works (Kondrat'ev, et al., 2016; Kondratiev, et al., 2022; Evdokimov, et al., 2024) non-destructive testing methods are analysed and methods of recognition of

technical condition of mining equipment are created. The works (Kondrat'ev, et al., 2022; Karlina, et al., 2023; Malozyomov, et al., 2024a; Malozyomov, et al., 2024b) describe the experience of operation including repair of mining equipment.

Table 1 presents failures and malfunctions of elements of automobile engines of the firm "Caterpillar" taking into account the coefficient of work in the conditions of the quarry.

Table 1 - Failure statistics of Caterpillar water supply elements over 10 years of operation, taking into account the coefficient of application of work in quarry conditions

Engine model	Node name	Number of failures	Operating time, hours	Cost of part(s), RUB
CAT C32	Fractured connecting rod of cyl. no. 4. Caused replacement of the cylinder block	2	22300	Cylinder block - 22 000 000 p.
	TC cartridge failure	12	8200	Cartridge - R850,000.
	Nozzle pump	6	6800-12000	Nozzle pump - 230 000 p.
	Loss in TC seals	4	22000-17200	Cartridge - R450,000.
	Fastening bolt pump nozzle	6	3000-18500	Nozzle pump - 230 000 p.
	Failure of electrical wiring	10	0-16000	
CAT C32	Failure of the pump nozzle mounting bolt	2	12000	Nozzle pump - 230 000 p.
	Valve mechanism	1	15600	Kingpin - 100,000 p.
	Gas compensator	26	13000-17000	120 000 p.
	Failure of the cylinder head mounting bolt	2	12000	23 000 p.

Fig. 2 shows that the majority of failures occur in the supercharger system and the engine timing mechanism. As examples, let's consider some failures on CAT engine systems.

Theoretical Provisions. Let's consider one of the examples of failure of automobile engine of the quarry dump truck of firm Caterpillar of mark C32 with capacity 1200 kW with working time of 3074 hours. To investigate the nature of engine failure, it is necessary to analyse and apply the coefficient of operation in quarry conditions and completeness, according to its purpose (Bosikov, et al., 2023; Gridina, et al., 2023; Gridina, et al., 2022; Zharikov, et al., 2022). The engine is equipped with a modern local system of control and diagnostics of operating parameters during operation (Martyushev, et al., 2023; Rodionov, et al., 2022). All information obtained during operation is stored and processed in the electronic control unit (ECU).

The BEU can fulfil the following functions:

- collects and stores information from all installed sensors on the engine;
- stores the engine operating history, including maintenance, repairs and accidents for the entire period of operation.
- controls the engine by changing the cycle fuel flow rate and performs diagnostic tests to detect malfunctions and errors in the fuel system components;

- makes decisions if certain parameters reach permissible limits and performs actions: "WARNING", "LOAD REDUCTION", "STOP".

Modern electronic control system of "Caterpillar" company is shown in Fig. 2.

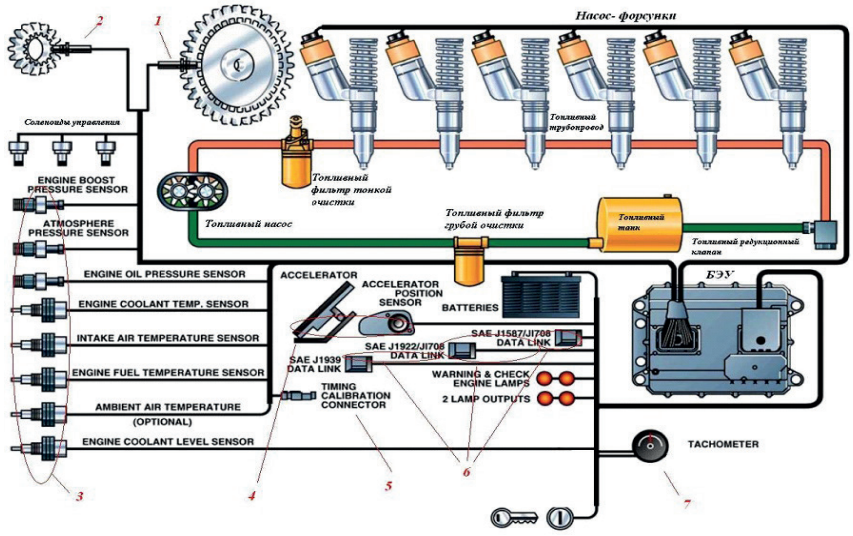


Fig. 2. Electronic engine management system C3:
1 - crankshaft speed sensor; 2 - camshaft position sensor; 3 - controlling elements of the control system; 4 - speed regulator; 5 - connecting output for the calibration device; 6 - SAT data transmission channel; 7 - engine speed indicator

The engine under test has sensors (analogue and digital sensors), which transmit a signal to the ECU (Table 2). Analogue sensors continuously monitor temperature and pressure, and send information to the electronic system in the form of changing voltage in the direct current (DC) network. Table 2 shows that all sensors are labelled, have an operating range and a measurement error of less than 5 %.

Caterpillar software licence CAT ET installed on the operator's service computer. In order to read and transmit all the data described above, it is necessary to connect to the ECU through an adapter (Fig. 3).

Table 2 - Main characteristics of sensors of standard control and measuring devices, used in the system "Caterpillar" automotive engine of a dump truck

Sensor name	Measuring range	Output signal	Measurement error
MBS 5100 pressure transmitters	0-600 bar	4-20 mA	0.5% of the upper measuring limit
Low pressure transmitter MBS 9300	40-250 mbar	4-20 mA	at 25 °C from ≤ ± 0.5 ≤ ± 2.0 %
Temperature sensor MBT 5560	-50-200 °C	4-20 mA or proportional 10 - 90% of supply voltage	< ± 1.0% of the upper measuring limit

MBT CAT temperature sensor	0-900° C	4-20 mA or proportional 10-90% of supply voltage	< ± 1.0% of the upper measuring limit
Crankshaft speed sensor	0-2400 min^{-1}	12.5 V single pole magnetic generator	< ± 1.0% of the upper measuring limit

Fig. 3. Location of connection of elements of the BEU system:
1 - service computer with CAT software; 2 - adapter connecting the engine ECM and the computer; 3 - electronic control unit ECM

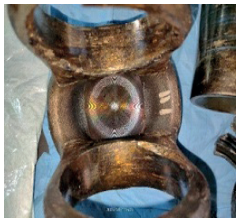
Results and Discussion. In this connection, visual and parametric inspection and defecting were performed to analyse the accident. The results of computer diagnostics obtained by the authors, 20 hours before the accident, allowed us to compare the same values taken immediately after the accident.

The following types and methods of non-destructive testing were applied to identify the causes of the failure of the automotive engine of the C32 dump truck: visual inspection and defection, dismantling and computer diagnostics.

Visual inspection and defection: external inspection of engine, defecting part of exhaust and intake manifold; defecting oil cover, cylinder No. 4; defecting parts and assemblies of valve train mechanism; defecting plate "spacers" of cylinder cover No. 4; defecting block inspection cover, cylinder No. 4; inspection, defecting of the block in the area of the 4th cylinder, the block has significant destruction in the area of water cooling channels, oil line, seating places of the cylinder sleeve; lower cover and connecting rod bearing, cylinder No. 4; defecting of the cylinder piston group, cylinder No. 4: - piston, pin, connecting rod, bushing; oil nozzle (tab. 3).

Table 3 - Photos of faulty parts and their defect detection of an emergency automobile engine of a C32 dump truck with a power of 1200 kW

№	Fault photo	Note
1		the firing section of cylinder head No. 4 shows significant piston impact marks and significant mechanical damage, valve seat failures

2		Bearing condition is satisfactory, there are operational rubs
3 4	 	piston: the head has significant mechanical damage to the firing part; traces of increased temperature due to forced rubbing on the cylinder sleeve, complete destruction of the skirt.
5	 	
6	 	shows signs of overheating on the surface
7	 	connecting rod: has significant body fractures in more than four parts; there are traces of connecting rod fracture in the head bearing area (rough surface, crystalline structure, virtually no plastic deformation)

8			complete destruction, rubbing marks on the bushing fragments

Dismantling of engine parts: part of the exhaust and intake manifold; oil cover of the valve train mechanism, cylinder No. 4; dismantling of the valve train mechanism; dismantling of the cylinder cover, cylinder No. 4; defecting the firing part of the cylinder cover; dismantling of the "spacer" plate of the cylinder cover No. 4; dismantling of the lower connecting rod bearing cover; cylinder piston group, cylinder No. 4: piston, pin, connecting rod, bushing (Table 3).

Computer diagnostics of dump truck engine showed the following engine failure errors: E173 High Exhaust Temperature Warning; E101 High Crankcase Pressure Warning; E020 High Engine Oil Temperature Warning; E021 High Exhaust Temperature Derate; E013 High Crankcase Pressure Shutdown.

The following was detected during the engine defect test:

1. The firing section of cylinder head No. 4 shows significant piston impact marks and significant mechanical damage, valve seat failures.

2. The condition of the bearing is satisfactory; piston: the head has significant mechanical damage to the firing part; traces of increased temperature due to forced rubbing against the cylinder sleeve, complete destruction of the skirt; pin: has traces of overheating on the surface; connecting rod: has significant destruction of the body in more than four parts; in the area of the head bearing there are traces of rupture of the connecting rod (rough surface, crystalline structure, virtually no plastic deformation); sleeve: complete destruction.

3. Rubbing marks are observed on the sleeve fragments. The block has significant destruction in the area of water cooling channels, oil line, cylinder sleeve seats; block oil nozzle is destroyed.

During inspection through the inspection hatch from the engine crankcase, "revealed" chipping of the lower edge of the cylinder sleeve adjacent cylinder #3, with cylinder #4.

Conclusion.

1. According to the results of inspection of parts and assemblies of the dump truck engine, analysis of the documents submitted on the date of the report, the damage to the parts of the engine cylinder No.4 described in the paragraphs of this report may be the result of violation of the integrity of the piston of the cylinder No.4 when the engine is operating at maximum load (100%$Ne_{ном}$) at a speed less than nominal (1528 min^{-1}), i.e. the mode of uncharacteristic load on the engine from the speed of rotation is possible (it is necessary to carry out additional research). Since the

piston is composite and has different metals in its arrangement (steel, aluminium), uneven rubbing against the cylinder mirror with the appearance of interatomic bonds in dissimilar materials occurred. According to the chronology of the next events, there is an increased temperature of the exhaust gases, which increases the overload mode of cylinder No. 4. Presumably, first of all, the piston wear parts get into the zone between the valve plate and the seat, there is a mechanical stress on the exhaust valves. The movement of the collapsing piston, there is a death of valves and jamming of the piston (in the course of movement from the TMT). The nature of the fracture of the connecting rod in the area of the head bearing shows that the rupture occurred instantly, riveting and fluidity of the metal observed in these places is minimal. Impact shears and shear lip are observed in the second fragment of the fractured connecting rod as a consequence of the fracture.

2 Based on the nature of destruction of: cylinder head, sleeve, piston and connecting rod it can be assumed that the accident of the dump truck engine occurred due to jamming and destruction of the piston as a result of temperature rise of the material of parts at an uncharacteristic load of $100\%Ne_{ном}$ from the engine speed close to the maximum (1528 min^{-1}). Due to low operating time of motor-hours the possible cause of piston destruction is factory defect of the part (piston).

3. As a result of inspection of cylinder No. 4 by the nature of fracture there is a need to defect the paired group No. 3 to make a representation of the destruction of parts and confirmation of the possible cause of failure of the automobile engine of the dump truck.

4. Car engine torsional vibration damper inspection.

5. To determine the suitability of the remaining parts of the engine (parts of the CSP, CMM, crankshaft, crank shaft, cylinder head, mounted mechanisms), it is necessary to perform a complete disassembly of the car engine of the dump truck and perform colour and magnetic defectoscopy, geometric belonging according to the nominal dimensions of the parts and assemblies under study.

6. In accordance with the purpose of the mechanism, to develop a methodology for monitoring the technical condition of thermophysical, vibration and tribological parameters of the car engine in operation, taking into account the coefficient of application of work in quarry conditions.

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