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METHODOLOGY FOR DIAGNOSTIC ASSESSMENT OF THE CONDITION AND WEAR OF ENGINE PARTS USING AN INDICATOR OF METAL AND SOLID PARTICLES IN EXHAUST GASES

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ABSTRACT The paper discusses a method for diagnostic assessment of the technical condition and wear of internal combustion engine parts based on analysis of the content of metal particles and solid inclusions in exhaust gases. The study is based on the analysis of the component composition of solid particles identified in the exhaust gases of mining equipment, in particular HITACHI EX1200 hydraulic excavators. It has been established that solid particles in the exhaust gases of modern engines contain wear products from cylinder-piston group parts, elements of neutralization systems, fuel additives, and engine oil components. Neutron tomography methods were used to determine the composition of the mineral fraction of solid particles, which includes calcium (37%), zinc (19%), silicon (15%), phosphorus (8%), and copper (2%). Criteria have been developed for assessing the technical condition of the main engine components based on the presence of specific indicator metals: iron, chromium, aluminum, copper, lead, tin, and other elements. It has been shown that elevated concentrations of metal particles indicate a malfunction of the engine's friction pairs and allow the need for unscheduled maintenance to be predicted. Using the example of the HITACHI EX1200 excavator, the relationship between the intensity of engine part wear and the frequency of unscheduled equipment downtime, reaching 111.17 hours per month, is demonstrated. The proposed diagnostic method helps prevent premature wear of the cylinder-piston group and reduce the operating costs of repairing mining equipment.

KEYWORDS Engine diagnostics, exhaust gases, particulate matter, metal inclusions, component wear, cylinder-piston assembly, wear indicators, technical condition, spectral analysis, mining equipment.

INTRODUCTION

The modern development of mining and transport machines is characterized by the constant complication of internal combustion engine designs and stricter requirements for their reliability and durability. In conditions of intensive vehicle operation, the problem of timely detection of malfunctions and assessment of the technical condition of engines without dismantling them becomes particularly relevant. Traditional diagnostic methods based on periodic inspection and measurement of engine performance parameters do not always allow the early stages of component wear to be detected, which can lead to sudden failures and emergencies.

In recent decades, methods of non-destructive testing of the technical condition of engines have undergone significant development, among which diagnostics based on the analysis of wear products in working environments occupies a special place. One of the most promising areas is the control of the content of metal particles and other solid inclusions in engine exhaust gases. This method is based on the fact that the processes of friction and wear of parts of the cylinder-piston group, gas distribution mechanism, and other engine components are accompanied by the formation of metal microparticles and wear products, which are partially carried away with the exhaust gas flow [1-5].

The use of metal and solid particle indicators in exhaust gases opens up new possibilities for early diagnosis of engine malfunctions. This method not only allows you to determine the fact of wear, but also to assess its intensity, locate worn parts by the nature and composition of particles, and predict the remaining service life of the engine. An important advantage of the method is the ability to monitor in real time without stopping the engine and without interfering with its design.

Despite its obvious advantages, the method of diagnostic assessment of engine condition based on metal indicators in exhaust gases has not yet found widespread practical application. This is due to a number of methodological and technical problems, including the need to take into account the influence of engine operating modes on particle concentration, the complexity of interpreting measurement results, and the lack of unified standards and criteria for assessing the condition of parts [6-9].

The purpose of this work is to systematize existing approaches to diagnosing the technical condition of engines by analyzing metal particles and solid inclusions in exhaust gases, to consider the physical basis of the method, to describe modern measuring equipment and methods for interpreting results, and to determine the prospects for the practical application of this diagnostic method in engine maintenance and repair systems [10-12].

MATERIALS AND METHODS

In the exhaust gases (EG) of modern engines, solid particles (SP) consist of engine wear products and neutralization systems, fuel and engine oil additive ingredients, as well as dust particles entering the cylinder with air. SP are a mixture of soot, unburned hydrocarbons, sulfates, and other inclusions. Studies of TPs using neutron tomography have shown that in most cases, the mineral fraction contains about 37% Ca, 19% Zn, 15% Si, 8% P, and 2% Cu [12,13,22].

The nature of wear on cylinder-piston group (CPG) parts (gearboxes, transmissions, bearings, friction pairs) depends on operating conditions. In most cases, the overhaul intervals for virtually all types of internal combustion engines (ICE) are determined by the intensity of wear on the CPG parts that are subject to the most severe operating conditions (the upper belt of the cylinder liner, piston rings, and ring grooves in the piston head). In general, the intensity of wear on ICE parts is determined by the influence of a large number of various factors: design and manufacturing features, materials and lubrication conditions of friction pairs, fuel and oil type, nature of application and power load values, relative speed and uniformity of movement of mating elements, temperature conditions of friction surfaces, air dustiness, etc. To determine the rate of wear of parts under certain operating conditions, it is necessary to obtain the dependence of the wear index (the mass of material removed from the friction surface, changes in geometric dimensions, mass of parts, etc.) on time [14,15].

An important diagnostic criterion for assessing the technical condition of internal combustion engines can be considered the qualitative and quantitative content of metal particles in the composition of the SP, indicating the malfunction of the engine's friction pairs, which could not be eliminated by using the most modern lubricants. This criterion is proposed to be used when studying the composition of the EG filtrate of mining equipment engines. The detection of excessive concentrations of metals (Fe, Ni, Cu, Al, Cr) in the oil, which are components of the engine and are identified in the form of organometallic chelate compounds with organic additives, may indicate the degree of wear of the engine components. Below are indicators of engine component wear based on metal impurities in the samples (Table 1) [14,17,18].

Additive indicators: calcium, magnesium, zinc, phosphorus, barium, boron.

Contamination indicators: silicon (dust), potassium, sodium, lubricant and coolant impurities (glycol) [14,19,21].

Thus, it can be estimated that the technical condition of mining equipment and vehicles can be diagnosed based on the concentrations of metals (iron, chromium, tin, aluminum, nickel, copper, lead, molybdenum), additives (calcium, magnesium, zinc, phosphorus, barium, boron) and contaminants (silicon (dust), potassium, sodium, lubricant and coolant impurities (glycol)) in engine oil are consistent with the results of research by the MIC GSM, which proposed diagnosing equipment wear based on metal impurities using the classic method in engine oil samples.

Table 1.

Indicators of engine component wear based on metal impurities in samples

Engine components	Wear indicators	Cause of wear
Bearings	Lead, Tin (Copper / Aluminum)	The surface of the bearings is coated with an alloy containing lead and tin. The presence of these two metals in the sample indicates the onset of bearing wear. If copper or aluminum is found together with lead and tin, this indicates increased bearing wear.
Inserts / Bushings	Lead, Iron	Wear and tear on these parts is usually accompanied by problems such as oil pressure loss, coking, and bearing wear.
Camshaft and valve block	Iron	If the sample contains iron levels exceeding normal wear and tear, this indicates wear on parts in the air supply system (camshaft, tappets, rocker arms, etc.).
Crankshaft	Iron, Lead, Tin, (Copper / Aluminum)	High concentrations of all these metals accompany crankshaft wear.
Cylinders	Iron, Chromium, and/or Aluminum	Chromium enters the oil from the piston rings, aluminum from the pistons, and iron from the cylinders. An accelerated increase in these concentrations indicates abnormal wear, engine overheating, oil contamination, and coking.
Pistons	Aluminum, fuel contamination, or dirt in the oil	Piston wear is caused by abrasive particles in oil contaminants. Another cause is engine overheating. In addition, fuel blow-by washes away the oil film and increases friction and, consequently, piston wear.
Piston rings	Chrome, fuel, or dirt	Ring wear is easily determined by the concentration of chromium and is caused by abrasive wear from dirt particles or fuel dilution of the oil.
Cylinder block / Intake manifold	Antifreeze impurity or Sodium / Potassium	Sodium, potassium, and sometimes silicon are components of antifreeze combustion products. They pass through the combustion chamber into the oil and serve as indicators of leaks in the cooling system.

Table 2.

Hydraulic excavator maintenance data

Field			**Excavator**	**Garage No.**
Central-Northern Amantai Tau Quarry			**HITACHI EX-1200**	**6**
No	**Type of downtime**	**Type of downtime**	**Description of downtime code**	**Duration (in hours)**
1	Unplanned	Regarding the mechanical part	damage to the hydraulic system	2.75
3	Unplanned	Regarding the mechanical part	filter contamination (filter replacement)	1.00

7	Unplanned	Regarding the mechanical part	engine malfunction	2.00
8	Scheduled	technical maintenance	scheduled maintenance (TM)	12.00
9	Scheduled	technical maintenance	scheduled maintenance (TM)	12.00
10	Scheduled	technical maintenance	scheduled maintenance (TM)	12.00
11	Scheduled	technical maintenance	scheduled maintenance (TM)	12.00
12	Scheduled	technical maintenance	scheduled maintenance (TM)	6.25
13	Unplanned	Regarding the mechanical part	damage to the hydraulic system	2.17
14	Scheduled	technical maintenance	scheduled maintenance (TM)	4.33
15	Scheduled	technical maintenance	scheduled maintenance (TM)	7.50
16	Unplanned	Regarding the mechanical part	malfunction of the hydraulic system cooling system	8.83
17	Unplanned	Regarding the mechanical part	malfunction of the internal combustion engine cooling system	0.67
18	Scheduled	technical maintenance	scheduled maintenance (TM)	0.67
19	Unplanned	Regarding the mechanical part	damage to the hydraulic system	1.67
21	Unplanned	Regarding the mechanical part	damage to the hydraulic system	2.92
22	Unplanned	Regarding the mechanical part	engine malfunction	6.67
23	Unplanned	Regarding the mechanical part	engine malfunction	8.33
25	Scheduled	technical maintenance	scheduled maintenance (TM)	1.00
26	Unplanned	Regarding the mechanical part	filter contamination (filter replacement)	0.92
27	Unplanned	Electrical components	Electrical malfunction Up to 12V (electrical wiring malfunction, battery malfunction, lighting system malfunction, other electrical malfunctions)	2.58
				108,26

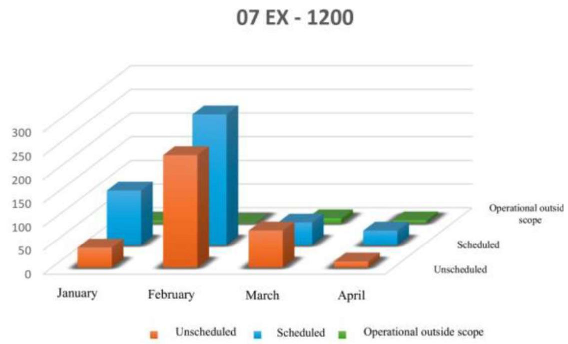
The study showed that the technical condition of internal combustion engines can be assessed based on the component composition and concentrations of solid and aerosol particles in exhaust gas condensate. To prevent premature wear of the cylinder head gaskets, it is recommended that engines with elevated concentrations of solid particles in the exhaust gas be sent for unscheduled maintenance.

Elevated concentrations of metal particles indicate a malfunction of the engine's friction pairs, which could not be eliminated by using the most modern lubricants.

Table 2 below shows the summary data from time studies and analysis of production reports on scheduled and unscheduled maintenance and downtime of the HITACHI EX1200 hydraulic excavator over one month of operation.

RESULTS AND DISCUSSIONS

Studies conducted using neutron tomography have shown that solid particles in the exhaust gases of modern engines have a complex multicomponent composition. The mineral fraction contains significant concentrations of calcium (about 37%), zinc (19%), silicon (15%), phosphorus (8%), and copper (2%).



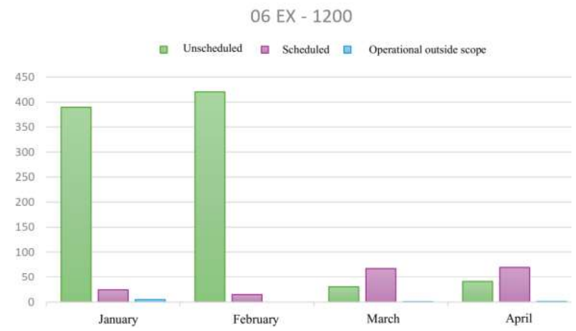


Fig. 1. Dependencies of downtime for the HITACHI EX1200 excavator

This distribution of elements is explained by the complex origin of solid particles: they are formed as products of engine wear, components of fuel and engine oil additives, particles from exhaust gas neutralization systems, as well as abrasive dust particles entering the cylinders with the air.

High calcium and zinc content is associated with the presence of detergent and anti-wear additives in engine oil, phosphorus is a component of anti-wear additives, and silicon indicates air pollution with abrasive dust, which is especially relevant for mining equipment operated in quarries.

Diagnostic criteria for assessing engine component wear

Based on an analysis of literature data and practical research, a system of indicators for wear of the main components of an internal combustion engine has been developed based on the content of specific metals in solid particles of exhaust gases:

Bearings. Lead and tin, which are components of anti-friction alloys in plain bearings, serve as wear indicators. The simultaneous detection of these metals indicates the initial stage of wear. The presence of additional copper or aluminum indicates increased bearing wear and approaching critical condition.

Cylinder-piston group. Key indicators are iron (cylinder wear), chromium (piston ring wear), and aluminum (piston wear). An accelerated increase in the concentrations of these metals indicates abnormal wear, which may be caused by engine overheating, oil contamination with abrasive particles, or coking of parts.

Gas distribution mechanism. Elevated iron content exceeding normal wear levels indicates intensive wear of air supply system components: camshaft, valve tappets, rocker arms, and other elements.

Crankshaft. High concentrations of a complex of metals—iron, lead, tin, copper, and aluminum—are a sign of wear on the crankshaft and its bearings, which poses a critical threat to engine performance.

Cooling system. The detection of sodium and potassium, sometimes in combination with silicon, indicates antifreeze leaks into the combustion chamber through the cooling system.

An important advantage of the proposed method is the ability not only to establish the fact of wear, but also to locate the specific worn component based on the characteristic spectrum of indicator metals.

Correlation of diagnostic results with operational data

Analysis of time-based maintenance data for the HITACHI EX1200 hydraulic excavator over a one-month period of operation at the Central-North Amantaitao quarry revealed a significant number of unscheduled downtimes related to internal combustion engine malfunctions.

The total downtime was 108.26 hours per month, of which:

Internal combustion engine malfunctions — 16.67 hours (3 cases)

Internal combustion engine cooling system malfunctions — 0.67 hours

Filter contamination — 1.92 hours (2 cases)

Hydraulic system damage — 9.5 hours (4 cases)

Hydraulic system cooling system malfunctions — 8.83 hours

Scheduled maintenance required 54.08 hours, which is almost half of the total downtime.

The frequency of unscheduled engine repairs (on average once every 10 days) correlates with the results of diagnostics based on the analysis of solid particles in exhaust gases, where increased concentrations of metals indicating wear of the cylinder-piston group were recorded.

Practical application of diagnostic methods

The study showed that the diagnosis of the technical condition of engines based on the analysis of the component composition and concentrations of solid particles in the condensate of exhaust gases is consistent with the results of the classical method of diagnosing equipment wear based on metal impurities in engine oil samples used by the International Research Center for Fuels and Lubricants.

However, the exhaust gas analysis method has a number of significant advantages:

The ability to perform diagnostics without stopping the engine

No need to take oil samples

Faster detection of wear products that immediately enter the exhaust gases.

Continuous monitoring of technical condition

This method is particularly relevant for mining equipment operated in conditions of high air dust content, as it allows the impact of abrasive wear to be assessed based on the silicon content in solid particles.

Recommendations for preventing premature wear

Based on the studies conducted, it has been established that engines with elevated concentrations of solid particles in exhaust gases should be sent for unscheduled maintenance to prevent catastrophic failures of the cylinder-piston group. The criteria for scheduling unscheduled maintenance are:

Exceeding the base levels of iron, chromium, and aluminum concentrations by more than 50%.

Detection of the simultaneous presence of lead, tin, and copper, indicating bearing wear.

A sharp increase in silicon content, indicating a malfunction of the air filters.

Presence of sodium and potassium, indicating leaks in the cooling system

The introduction of a continuous exhaust gas composition monitoring system will enable a transition from a scheduled preventive maintenance system to condition-based maintenance, which will significantly reduce operating costs and increase equipment availability.

CONCLUSION

The study of methods for diagnostically assessing the condition and wear of engine parts based on metal and solid particle indicators in exhaust gases allows us to draw the following conclusions:

Solid particles in the exhaust gases of modern engines have a multicomponent composition, including engine part wear products, fuel and oil additive components, neutralization system elements, and abrasive particles from the external environment. Neutron tomography allows reliable determination of the elemental composition of the mineral fraction, with a predominance of calcium (37%), zinc (19%), silicon (15%), phosphorus (8%), and copper (2%).

A system of metal indicators has been developed to diagnose wear in the main engine components: iron, chromium, and aluminum for the cylinder-piston group; lead, tin, copper, and aluminum for bearings; iron for the gas distribution mechanism; sodium and potassium for the cooling system. This system not only allows the detection of wear, but also the localization of the damaged component.

The diagnostic method based on exhaust gas analysis is consistent with the classic method of engine oil analysis, but has a number of advantages: it does not require the engine to be stopped, provides a faster response to the appearance of wear products, and allows for continuous monitoring of technical condition.

Practical application of the method using the HITACHI EX1200 hydraulic excavator as an example showed a high correlation between elevated concentrations of indicator metals in exhaust gases and the frequency of unscheduled engine repairs. During one month of operation, 108.26 hours of downtime were recorded, a significant part of which was due to engine and cooling system malfunctions.

To prevent premature wear of the cylinder-piston group, it is recommended to implement a system for continuous monitoring of the composition of solid particles in exhaust gases, with the equipment being sent for unscheduled maintenance when critical concentrations of indicator metals are exceeded.

The method is particularly relevant for mining equipment operated in dusty conditions, where abrasive wear of cylinder-piston group components is the main factor determining the time between repairs.

The introduction of the proposed diagnostic method will allow a transition from a scheduled preventive maintenance system to maintenance based on actual technical condition, which will reduce operating costs, increase equipment availability, and prevent catastrophic engine failures. Further development of the methodology is linked to the development of automated systems for sampling and analyzing the composition of exhaust gases in real time, as well as the establishment of quantitative standards for maximum permissible concentrations of indicator metals for different types of engines and operating conditions.

DVIGATEL QISMLARINING HOLATI VA ESKIRISHINI DIAGNOSTIK BAHOLASH METODOLOGIYASI: CHIQINDI GAZLARDAGI METALL VA QATTIQ ZARRACHALAR INDIKATORI YORDAMIDA

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ANNOTATSIYA Maqolada ichki yonish dvigatelining qismlarining texnik holati va eskirishini diagnostik baholash usuli muhokama qilinadi, bu usul chiqindi gazlardagi metall zarralar va qattiq inklyuziyalar tarkibini tahlil qilishga asoslangan. Tadqiqot tog'-kon uskunalarining, xususan HITACHI EX1200 gidravlik ekskavatorlarining chiqindi gazlarida aniqlangan qattiq zarrachalarning tarkibiy tuzilishini tahlil qilishga asoslangan. Ma'lum bo'ldiki, zamonaviy dvigatellar chiqindi gazlaridagi qattiq zarrachalar silindr-porshen guruhi qismlarining ishqalanish mahsulotlari, neytrallash tizimlari elementlari, yoqilg'i qo'shimchalari va dvigatel moyi komponentlarini o'z ichiga oladi. Qattiq zarrachalarning minerallar fraksiyasining tarkibini aniqlash uchun neytron tomografiya usullari qo'llanildi; u kalsiy (37%), rux (19%), kremniy (15%), fosfor (8%) va mis (2%) ni o'z ichiga oladi. Asosiy dvigatel komponentlarining texnik holatini baholash mezonlari ma'lum ko'rsatkich metallar – temir, xrom, alyuminiy, mis, qo'rg'oshin va boshqa elementlarning mavjudligiga asoslanib ishlab chiqilgan. Metall zarrachalarning yuqori konsentratsiyalari dvigatelning ishqalanish juftliklarining nosozligini ko'rsatishi va rejalashtirilmagan texnik xizmat ko'rsatish zarurligini oldindan bashorat qilish imkonini berishi aniqlangan. HITACHI EX1200 ekskavatori misolida dvigatel qismlarining eskirish intensivligi bilan rejalashtirilmagan uskuna to'xtab qolish chastotasi o'rtasidagi bog'liqlik, oyiga 108,26 soatgacha yetishi namoyish etilgan. Taklif etilgan diagnostika usuli silindr-porshen guruhining muddatidan oldin eskirishini oldini olish va kon uskunalarini ta'mirlash xarajatlarini kamaytirish imkonini beradi.

KALIT SO'ZLAR Dvigatel diagnostikasi, chiqindi gazlar, qattiq zarrachalar, metall aralashmalar, komponentlarning eskirishi, silindr-porshen guruhi, eskirish ko'rsatkichlari, texnik holat, spektral tahlil, tog'-kon uskunasi.

МЕТОДИКА ДИАГНОСТИЧЕСКОЙ ОЦЕНКИ СОСТОЯНИЯ И ИЗНОСА ДЕТАЛЕЙ ДВИГАТЕЛЯ ИНДИКАТОРОМ МЕТАЛЛА И ТВЁРДЫХ ЧАСТИЦ В ОТРАБОТАННЫХ ГАЗАХ

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АННОТАЦИЯ В статье рассматривается метод диагностической оценки технического состояния и износа деталей двигателя внутреннего сгорания на основе анализа содержания металлических частиц и твердых включений в выхлопных газах. Исследование основано на анализе компонентного состава твердых частиц, выявленных в выхлопных газах горной техники, в частности гидравлических экскаваторов HITACHI EX1200. Установлено, что твердые частицы в выхлопных газах современных двигателей содержат продукты износа деталей цилиндро-поршневой группы, элементов систем нейтрализации, присадок к топливу и компонентов моторного масла. Для определения состава минеральной фракции твердых частиц использовались методы нейтронной томографии, которые показали, что она включает кальций (37 %), цинк (19 %), кремний (15 %), фосфор (8 %) и медь (2 %). Разработаны критерии оценки технического состояния основных компонентов двигателя по наличию определенных индикаторных металлов: железа, хрома, алюминия, меди, свинца, олова и других элементов. Показано, что повышенная концентрация металлических частиц свидетельствует о неисправности фрикционных пар двигателя и позволяет прогнозировать необходимость внепланового ремонта. На примере экскаватора HITACHI EX1200 продемонстрирована взаимосвязь между интенсивностью износа деталей двигателя и частотой внеплановых простоев оборудования, достигающей 108,26 часов в месяц. Предложенный метод диагностики помогает предотвратить преждевременный износ цилиндро-поршневой группы и снизить эксплуатационные расходы на ремонт горнодобывающего оборудования.

КЛЮЧЕВЫЕ СЛОВА Диагностика двигателей, отработанные газы, твёрдые частицы, металлические включения, износ деталей, цилиндро-поршневая группа, индикаторы износа, техническое состояние, спектральный анализ, горная техника.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ И РАЗРАБОТКА ПОРШНЕЙ-УДАРНИКОВ ПОЛИКАТЕНОИДНОЙ ФОРМЫ ДЛЯ ПНЕВМАТИЧЕСКИХ ПЕРФОРАТОРОВ С ИСПОЛЬЗОВАНИЕМ КОМПЬЮТЕРНЫХ ПРОГРАММ

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АННОТАЦИЯ В статье рассматривается метод математического моделирования перехода от цилиндрической формы поршня-ударника к полукатеноидной геометрической форме. Переход между геометрическими формами описывается как процесс параметрической трансформации, основанный на непрерывных и гладких математических зависимостях, обеспечивающих сохранение основных геометрических характеристик исходной формы и постепенное формирование параметров конечной геометрии. Особое внимание уделено обеспечению непрерывности и дифференцируемости геометрической модели, что позволяет исключить появление резких изломов и геометрических разрывов в зоне перехода. На основе разработанной математической модели с помощью компьютерных программ была создана полукатеноидная часть поршня-ударника. Предложенная модель может быть использована при проектировании ударных элементов горных машин для оптимизации их геометрии, снижения концентрации напряжений и улучшения распределения нагрузок в конструкции.

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