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January 16. 2004

SEAL:
(NAVY ACADEMY)

REPORT
on Research Work

"Study of Suprotec Tribotechnical Compound Influence on Internal Combustion Engine Performance Indicators:
NIR 3505 hd

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ОТЧЕТ
о научно-исследовательской работе

"Исследование влияния триботехнического состава "Супротек" на показатели работы ДВС"

НИР 3505 хд

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SUMMARY

The Report contains 57 pages, 26 figures, 25 tables, 10 appendices.

Keywords: friction, wear, friction machine, diesel, lubrication oil, tribotechnical compound, effectiveness, antifriction properties, antiwear properties.

Object of study: an internal combustion engine.

Purpose of work: comparative analysis of an engine performance indicators with standard lubrication oil and the SUPROTEC tribotechnical compound based on the results of 2 hours tests of a diesel 8.5/11. determining effectiveness of this compound.

The antifriction properties of SUPROTEC were determined by mechanical efficiency of the engine. The antiwear properties of oil additives were determined by the wear of the diesel cylinder liners, the wear of piston rings and connection rod bearing shells. Wear assessment was performed using the method of artificial radioactive bases (IRAB), the method of cutting pits in cylinder liners and piston rings and piston rings micrometering. Indicator values were determined with the help of an IVK-1 PC-based complex, an L-154 ADC, a cylinder pressure transducer and induction crank-shaft position sensors. Exhaust gases emissions were determined by the GATU instrument.

The obtained results are a stage in a series of studies of supplementary functional additives to internal combustion engine lubrication oil on the basis whereof it is possible to select the most effective and feasible additives for ship engines of the RF Navy.

CONTENTS

LIST OF ABBREVIATIONS AND CONVENTIONAL DESIGNATIONS

Cfr. - friction coefficient;

M - frictional resistance moment;

P - load acting on a sample;

ARAB - artificial radioactive bases;

Ne - effective engine horsepower;

MCC - measuring computer complex;

ADC - analog/digital converter;

φ - crankshaft angle;

η_i - indicated efficiency;

η_m - mechanical efficiency;

η_i - effective efficiency;

Pz - maximum combustion pressure;

Pc - compression pressure.

Pi – average indicated pressure,

ge - specific effective fuel consumption,

φz- Pz angle, crank angle degrees;

dp/dφ - pressure increase rate

φia - ignition angle, crank angle deg.

φmax - maximum φmax - crank angle deg. (angle of maximum cylinder pressure increase range)

m - combustion law exponent powers (combustion law characteristic);

φm - relative crank angle at which the combustion rate is the maximum one;

xm - relative amount of emitted heat at the moment of φm;

(dx/dφ)max - maximum fuel combustion rate;

φzr - combustion duration

φ1/2 - duration of combustion of 1/2 of fuel.

INTRODUCTION

The principal factor limiting the durability of an internal combustion engine is the wear resistance of its components, namely, the cylinder-piston group components and the crankshaft. Wear resistance may be increased using various methods. The majority of them is used at the stage of engine manufacture or overhaul. The solution of this problem at the stage of operation of existing engines is of a special interest from the economical and practical points of view. Only two trends can be followed in this case: creating new lubricants or using additives, whereupon the latter is more feasible economically and less labor intensive practically.

The following types of antifriction and antiwear lubrication oil additives are known:

- additives that shape a thin layer of soft metals on the friction surfaces in the process of a facility running; this layer separates these surfaces (e.g., RIMET, Lubrifilm);
- additives activating lubricating oil adhesion to the friction surface (surfactants), such as Aspect-Modificator, PMF-200. Slider-2000;
- additives forming polymer films on the friction surface ("Forum");
- metal conditioners generating an ultra-thin layer of a new separating metal on the friction surfaces in the process of physico-chemical transformations (ER, MILITEK, FENOM), etc.

Soft metals (molybdenum, tin, copper, silver, etc.) can be introduced into the friction zone either in molecular finely dispersed form, or on the ion level as a result of chemical reactions between lubrication oil components and the source of soft metal.

The implementation of the first method involves two problems: 1) creating a stable suspension of thin particles of soft metals; 2) the ratio between the allowable concentration of such metals in the circulating oil and the concentration that is sufficient to ensure the cladding effect at least for the useful life period of lubrication oil.

Thus, even in case these problems are solved successfully, the efficiency of such additives is extremely limited as regards their service life. Besides, a thin separating layer of soft metal does not protect the friction surface from scoring in emergency cases, i.e. when lubrication circulation is stopped.

The second method involves the implementation of selective transfer; for the time being, this process is purely random and manifests itself very rarely.

Additives enhancing lubrication oil adhesion to the friction surface may be very effective as regards their antiwear and especially antiscoring characteristics. But they have major shortcomings: 1) the impact of such additives continues only as long as they are present in the lubrication oil in a sufficient concentration; 2) as a rule, such additives are not antifriction, they are even capable of increasing friction resistance; 3) usually high concentrations of such additives can impact the lubrication oil rheology.

Because of complexity of physico-chemical transformation processes, metal conditioners are not universal as regards tribounit materials and running conditions, although they may be the most promising alternative.

In 1980-85. a group of Leningrad scientists that discovered the effect of low hydroxides on steel friction laid the foundation for a new scientific field: geotriboenergetics [1. 2, 3. 4].

The effect was discovered by chance when analyzing the technical condition of wheel pairs of mine cars used at ore deposits. The powder formed in a wheel pair by abrasion and subsequently named geomodifier (a repair and restoration compound) has a number of unique properties. One of them is to change the nature of interaction between rubbing pieces.

The most well-known tribotechnical compounds: NIOD, RIU-11. MMT TSP PZS, RVS, KhADO, FORSAN, Live Metal, SUPROTEC, etc. These are additives based on natural ultrabasic rock minerals [5]. As they get into a friction zone, they make structural changes to the friction surface that are able to modify it in a tribotechnically favorable way.

The principal advantages of these compounds are:

- their ability to form a new surface on the original material. The structure, macro- and microparameters of this surface correspond to the friction unit materials, the lubricant and the unit operation conditions in the most optimum way (from the tribotechnical point of view).
- the newly created layer consists of the principal friction material and has a high adhesion strength (corresponds to the base material), a high oil-retaining capacity (10 and more times) and enhanced microhardness (20-40% higher).
- reduced friction coefficient, and therefore, mechanical losses;
- environmental friendliness of the natural product.

The most distinctive feature o mineral additives is the possibility of engine, mechanism and device friction units for account of initiation of self-organizing triboprocesses in the direction of restoration of physical bonds between the surface layer and the finely dispersed medium of the base material in the lubricant medium of internal combustion engines, mechanisms and devices.

Geometrical dimensions of worn-out parts are restored via self-organizing processes from the tribounit base material and the material of the finely dispersed natural mineral.

Usually, the stationary state of a tribounit boundary layer corresponds to a dynamic balance between the processes of destruction and restoration of physical bonds. A worn-out part is in a cyclical state of the processes of loosening, dispersion and rotative motion of wear particles [6]. Adding finely dispersed (0.01-5 μm) SUPROTEC powder to an engine, mechanism or device standard lubricant in the amount (0.01-0.4 weight %) brings about the disturbance of the abovementioned dynamic balance towards restoration of physical bonds.

Self-organization lies in the hereditary "memory[6] of a material. Al, Si, Mg and Fe present in the powder are catalysts of building up a layer with a high number of free bonds bonding the "lost" material from the dispersed medium.

The economic effect of introduction of the additive may amount to hundreds of millions of rubles, profit on every ruble invested into the geotriboenergetics problem may amount to 100 rubles.

1. EXPERIMENTAL STUDIES OF A 2TCh8.5/11 ENGINE RUNNING ON STANDARD LUBRICATION OIL

1.1 Triboprocesses Modeling on a Friction Machine

The tribotechnical compound is a finely dispersed powder (0.01-7 μm) prepared on the base of serpentine mineral containing talc-chlorite-carbonate shale with a phase composition presented in Table 1.

Table 1

Phase composition of powder

Discovered phase	Chemical formula	Content, %
Serpentine (antigorite)	$Mg_6\{Si_4O_{10}\}(OH)_8$	10 - 16
Talc	$Mg_3Si_4O_{10}(OH)_2$	18 - 20
Chlorite	$Mg_3Fe_2Al_2Si_3O_{10}(OH)_8$	20 - 25
Calcite	$CaCO_3$	40 - 45
Catalysts	-	5 - 7

Unlike enstatite, fayalite [7] and magnetite [8], calcite that is used as the abrasive fraction of the proposed compound has a structure (banded silicate) that allows to obtain thinly dispersed powder from the crushed mineral without additional (more long-term) crushing. As a result, an effective size fraction (3-5 μm) of chlorite and antigorite is retained; they will carry out the second stage of surface modification. Unlike compound [7], the fine fraction of tremolite allows to use it in lubricants without limitations (without draining oil or replacing grease).

SUPROTEC is added to the standard lubrication oil in internal combustion engines, mechanisms and devices in the amount of 0.02-0.2 weight %, to greases in the amount of 0.5-1.5 weight %, or is used as a solid lubricant.

The tribotechnical compound has undergone preliminary tests on an II5018 friction machine (Figure 1).

Registered parameters:
- frictional resistance moment M (N*m);
- oil temperature in the chamber T (°C);
- number of cycles N.

The kinematic diagram of the friction machine is presented in Figure 1.

Kinematic diagram of an II5018 friction machine

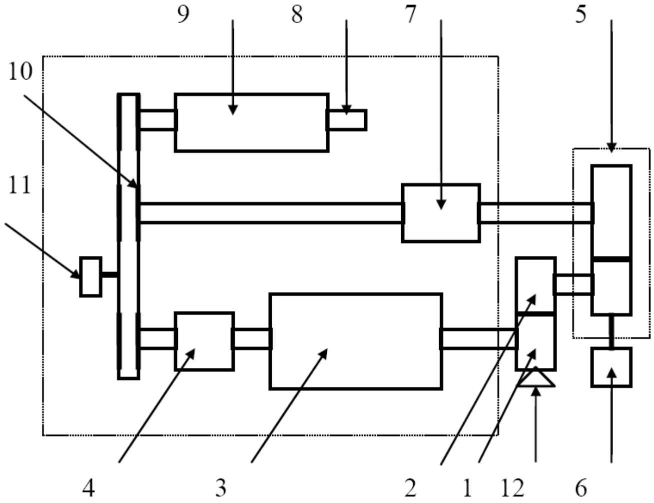


Figure 1

1 - sample; *2* - countersample; *3* - spindle; *4* - torque sensor; *5* - carriage; *6* - load sensor; *7*- clutch; *8* - rotation velocity sensor; *9* - electric motor; *10* - belt transmission; *11* - cycle sensor; *12* - temperature sensor.

The wear of a sample and a countersample was determined by weighing them before and after the test on a VRL-200 analytical scale with an accuracy to 0.3 mg.

Friction coefficient *Cfr* is determined by Formula 1.

$$Km\text{p}= \frac{M}{P * R}, \qquad (1)$$

where: M is frictional resistance moment (N* m);

P is normal disk load (N);

R is the moving disk radius (m).

The tests of the SUPROTEC tribotechnical compound were carried out on an II5018 friction machine by comparing the base M12G$_2$K oil with the SUPROTEC tribotechnical compound (2 weight %).

Test pattern: "disk on fixed disk" (moving disk: d=50. h=12, fixed disk: d= 40. h=10)

Material: - St.30 steel

Operation conditions: - n=1600 min $^{-1}$ (V= 4.19 m/s), Load P = 100 N;
- n =700 min $^{-1}$ (V= 1.83 m/s), Load P = 400 N;
- n =700 min $^{-1}$ (V= 1.83 m/s), Load P: until scoring.

The wear of the sample (the moving disk - Δmo) and the countersample (the fixed disk Δmk/o) was determined by weighting them before and after the tests on a VRL-200 analytical scale with an accuracy to 0.5 mg.

For modifying the surface layer as per the SUPROTEC technology, the sample and the countersamples were preliminarily run in during 20 thous. cycles (1.6 h) at 200 min^{-1} and at varying loads (0-800 N) in $M12G_2K$ oil with SUPROTEC tribotechnical compound (2%).

The results of the tests are presented in Table 2.

Table 2

Comparative tribotechnical characteristics

№ n	V m/s	P H	N $*10^3$	t min.	Medium in the oil chamber	Cfr.	T °C	Δm o mg	Δm k/o mg
1	1600	100	100	60	$M12G_2K$ oil	0.18	55	-1.1	-0.5
2	1600	100	100	60	$M12G_2$ oil with SUPROTEC (2 %)	0.14	59	-0.3	-0.1
3	700	400	50	70	$M12G_2K$ oil	0.10	61	-1.3	-0.4
4	700	400	50	70	$M12G_2K$ oil with SUPROTEC (2 %)	0.08	62	-0.2	-0.2

The SUPROTEC tribotechnical compound tests with the purpose of finding out whether subsequent sample running without oil is possible have given the following results (Table 3. 4)

Table 3

Sample running in clean $M12G_2K$ oil

№ n	V m/s	P H	N $*10^3$	Cfr.	T °C	Δm o mg	Δm k/o mg
1	1600	100	0	0.12	20	-	-
2	1600	100	10	0.14	21	-	-
3	1600	100	40	0.18	23	-	-
4	1600	100	50	0.2	23	-	-
Sample running without oil							
5	1600	100	50	After oil draining - scoring after 51.000 cycles			

Table 4

Sample running in $M12G_2K$ with SUPROTEC -2 %

№ n	V m/s	P H	N $*10^3$	Cfr.	T °C	Δm o mg	Δm k/o mg
1	1600	100	0	0.20	23	-	-
2	1600	100	10	0.16	29	-	-
3	1600	100	40	0.14	32	-	-
4	1600	100	50	0.14	38	-	-
Sample running without oil, with the additive							
5	1600	100	50	0.14		-	-
6	1600	100	60	0.14		-	-
7	1600	100	70	0.16		-	-
8	1600	100	80	0.16		-	-
9	1600	100	90	0.16		-	-
10	1600	100	100	0.18		-1.6	-1.8

Thereby, 30 minutes' running of a sample with $M2G_2K$ and SUPROTEC tribotechnical compound allows the sample to run for 30 minutes within the framework of the allowable wear conditions. Further testing without oil are infeasible since this time period is sufficient to detect a breakdown. 4-5 times increase of wear and 30% increase of friction resistance as compared with running the samples without draining oil bear witness to the start of catastrophical processes that will bring about scoring at a certain moment.

The SUPROTEC tribotechnical compound tests for maximum loads (up to scoring) had the following results (Tables 5. 6)

Table 5

"Clean" $M12G_2K$ oil scoring tests

N $*10^3$	n min^{-1}	P H	Cfr.	T °C	Notes
0	700	100	0.220	23	normal running
5	700	200	0.180	32	normal running
10	700	300	0.140	38	normal running
15	700	400	0.115	44	normal running
17	700	500	Scoring after 17000 cycles		

Normal load equal to 700 N on 10 mm^2 contact area corresponds to 700 kg/cm^2 specific load and exceeds the maximum load causing scoring on "clean $M12G_2K$ oil by 40%.

Table 6

Scoring tests of $M12G_2K$ oil with 2% SUPROTEC

N $*10^3$	n min^{-1}	P H	Cfr.	T °C	Notes
0	700	100	0.160	22	normal running
5	700	200	0.110	30	normal running
10	700	300	0.100	37	normal running
15	700	400	0.090	40	normal running
20	700	500	0.080	42	normal running
25	700	600	0.075	46	normal running
30	700	700	0.075	49	normal running
33	700	700	Scoring after 33000 cycles		

CONCLUSIONS:

1. The results of the preliminary tests of SUPROTEC tribotechnical compound have confirmed a specific feature of samples tests on a friction machines using geomaterials: lower temperatures and specific pressures as compared to actual facilities (internal combustion engines, transmissions, etc.); this fact brings about a reduction of probability of modified layer formation. Therefore, the actual tests were performed with samples that had been run in according to the procedure presented above.

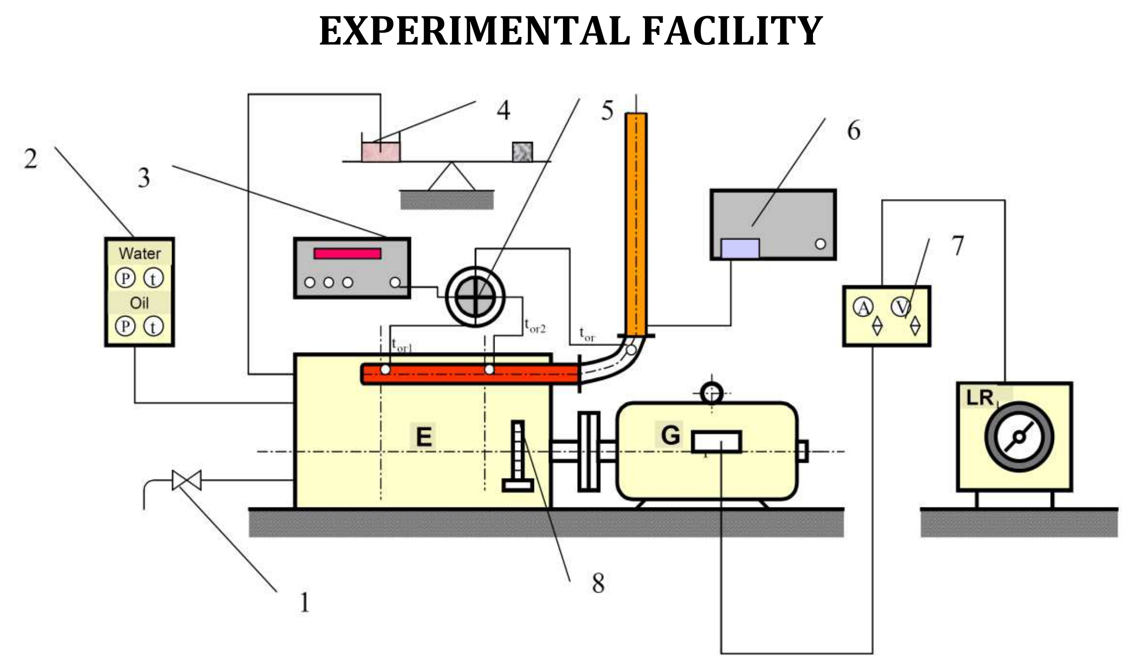
2. Adding 2% of SUPROTEC tribotechnical compound to $M12G_2K$ oil brings about 3-4 times reduction of wear and 20% reduction of losses under various test conditions, allowing to increase the useful life of the respective friction unit and to reduce fuel or electric energy consumption.

3. A layer modified according to the SUPROTEC technology protects a friction surface in case of emergency loss of lubricant for a period of time that is sufficient to detect such a breakdown, although wear increases sharply in this case. As compared to a friction unit running under normal conditions (with a lubricant), wear increases 4-5 times, but in absolute values such a wear reduces the friction unit service life by fractions of percents.

4. Adding 2% of SUPROTEC tribotechnical compound to $M12G_2K$ oil brings about a 40% increase of the maximum load causing scoring as compared to "clean" $M12G_2K$. This allows to create normal friction conditions for critical units without changing the type of lubrication oil.

1.2. Experimental Facility

We have chosen an experimental facility (Figure 2) based on a 2TCh8.5/11 mini diesel engine manufactured by the Dagdiesel plant. It is a four-tact, water-cooled, straight swirl-chamber diesel engine having 8.0 kW capacity at 1500 min^{-1}.



E - engine, G - PN-85 generator, LR - load rheostat, 1 - lubrication oil sample tap, 2 - instrument panel, 3 - V7-16 voltmeters, 4 - VTsN scale, 5 - switchboard, 6 - GATU gas analyzer, 7 - control and load monitoring panel, 8 - lubrication oil level gauge.

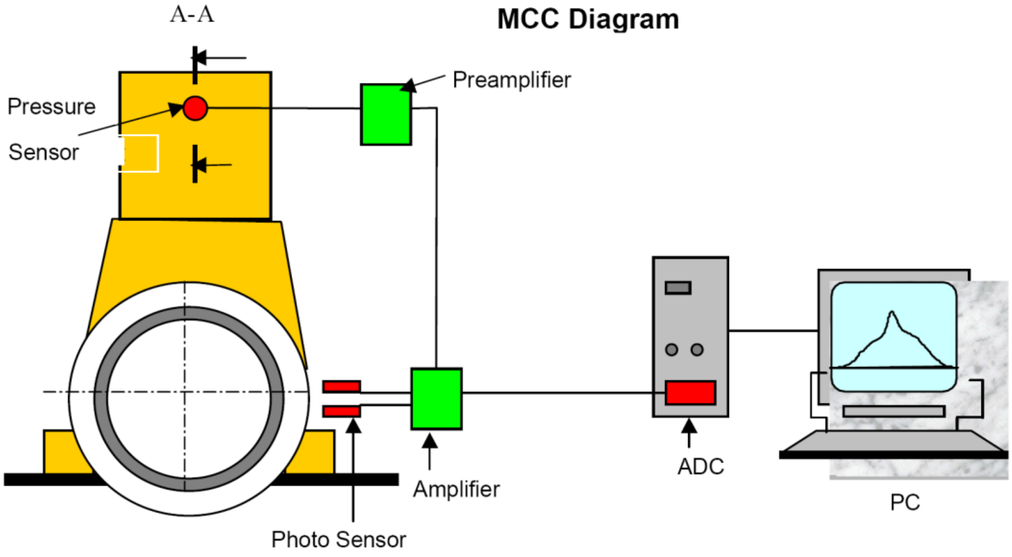
Figure 2

The engine drove a PN-86 generator, the load was adjusted by a ballast resistance and monitored by current parameters.

Fuel consumption was controlled by a VTsN scale and calculated by the time during which 50 g of fuel are consumed.

Burning oil consumption is determined by the readings of a level gauge during the engine running.

A measuring computer complex (MCC) used for studying the engine workflow; it allowed to obtain reliable information on the ground of gas pressure variation in a cylinder depending on the crank angle. This information is presented in a convenient form for using in any data or computational computer software. The process of information transfer between information media and software is effected automatically. The measuring computer complex designed by us (Figure 3) is a universal instrument; that is, it is capable of measuring any rapidly changing physical processes (pressures, temperatures, vibrations, etc.) preliminarily transformed into standard 0–5 V standard electrical signals.



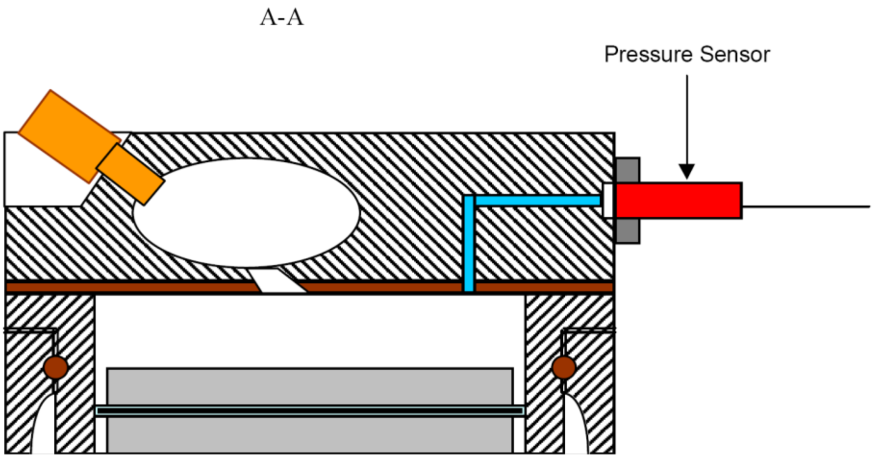


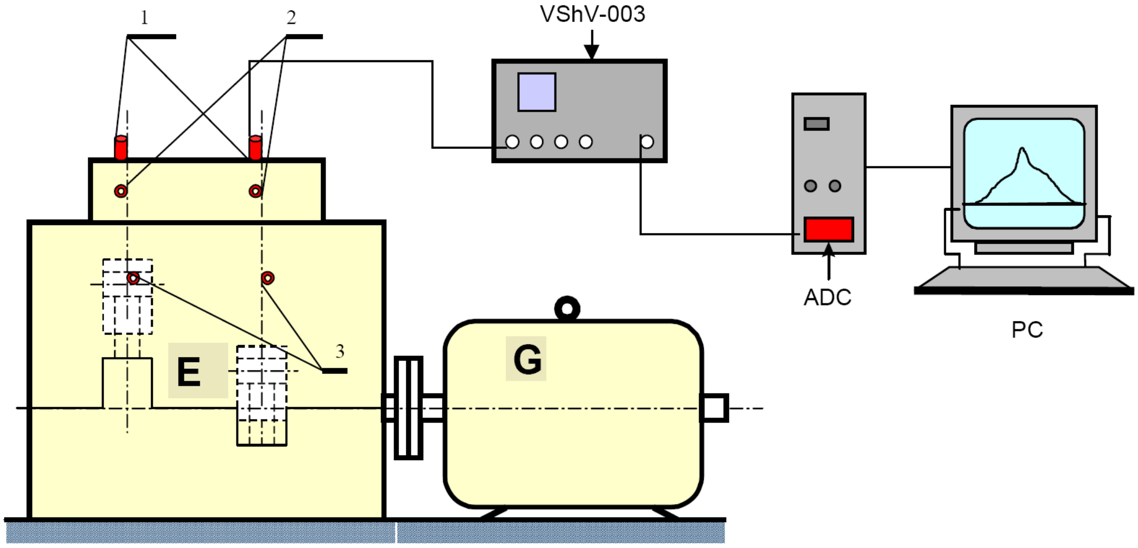
Figure 3

The measuring computer complex (MCC) consists of an analog/digital converter (ADC) in the form of a separate printed board installed in a computer. An uncooled semiconductor strain gauge manufactured by the GARANT company is connected to the 2TCh 8.5/11 diesel head end through a special channel bored in the cylinder head. Impulses corresponding to the crankshaft position are generated by an induction sensor.

Information on cylinder pressure depending on the crankshaft position is obtained through transforming physical processes of pressure and crankshaft rotation into electrical values and then amplifying these signals to a standard value of 0–5 V. Signals are generated as the sensor is scanned by the ADC master generator.

Data are transformed in a similar way when the engine vibrations are measured (Figure 4). D-11 piezotransducers were connected to the ADC via an interface device: VShV-003 analyzer. Such a design concept ensured the possibility of changing actual vibration accelerations depending on the crankshaft position.

VIBRATION-BASED DIAGNOSTICS DIAGRAM



E - Engine, G - PN-85 generator, VShV-003 - vibration signals amplifier, 1 - D-11 piezotransducers of vertical vibration components, 2 and 3 - horizontal vibration component sensors on the cylinder head and the cylinder block in the TC vicinity.

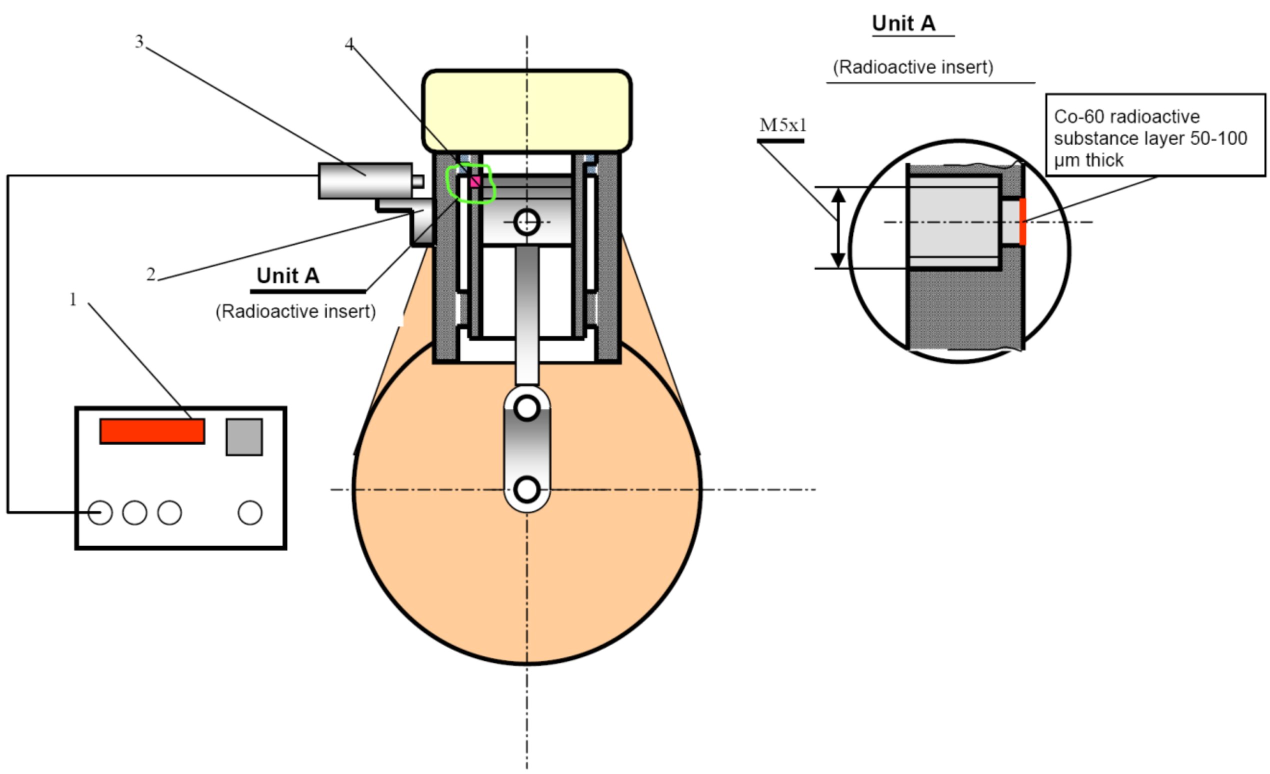
Figure 4

The physico-chemical and spectral analysis of lubrication oil was performed in respect of oil samples taken at the end of each day of the experiment using the oil analysis laboratory and a MFS-7M photospectrometer.

Exhaust gas emission was controlled by a GATU gas analyzer at the end of each day of work. Relative error in determining the exhaust gas composition does not exceed 2%.

The cylinder liners wear rate was assessed by the ARAB (artificial radioactive bases) method (Figure 5). For that purpose, the first cylinder liner was activated by an insert containing a radioactive source (Co^{60}) at the top compression ring reversal point. The liner activity reduction during a certain continuous running time with regard for autodisintegration was calculated on a PC with the help of a specially created software.

Engine Diagnostics Using Artificial Radioactive Bases (ARAB)



1 - 20046 RFT radiometer, 2 - bracket, 3 - SA sensor, 4 - radioactive insert (base)

Figure 5

Besides, cylinder-piston group wear was monitored at all stages using the following methods:

- cutting pits in cylinder lines by a UPOI instrument (8 pits on the ARAB mark level);
- cutting pits in piston rings by a UPOI instrument (7 pits);
- micrometering piston rings by an IZV-1 instrument (ring height and width);
- weighing piston rings on VLR analytical scales.

Accelerated test methods tried in academic studies were used extensively in experimental research.

The experiment included running in piston rings and cylinder liners until stabilization of cylinder liners wear (38 hours) at 50% load. Stage 1 - engine running on standard $M10G_2$ oil (50 hours) at 100% load, stage 2 - engine running on standard $M10G_2$ oil with 0.2% SUPROTEC (50 hours) at 100% load.

1.3 Determining Indicator, Effective, Economic, Lifetime and Environmental Parameters of an Engine

The following conditions were met at each stage with the purpose of reducing influence factor during comparative tests of $M10G_2$ lubrication oil and oil with SUPROTEC additive:

- running in the cylinder-piston group at 50% load until cylinder liners wear rate stabilization;
- equal running time at each stage (50 hours);
- engine running at equal loads (100%);
- equal time of cold engine starts (7 hours running);
- equal amount of fuel and lubrication oil.

The first stage of tests (engine running on standard lubrication oil) is presented in Table 7.

Table 7

Engine running on standard lubrication oil

Running time h	Power, kW	Wear 1 W µm	Exhaust gas temperature °C	Spec. eff. fuel consumption g/(kWh)	Spec. eff. oil consumption g/(kWh)
7	7.21	0.35	369	275.8	8.2
14	7.16	0.78	357	274.8	6.8
21	7.21	1.2	366	277.4	9.0
28	7.06	1.3	355	277.2	9.8
35	7.10	1.6	351	275.6	8.9
42	7.01	2,3	352	276.0	7.0
50	7.15	2,65	357	279.7	8.0
Average wear rate Vav= 0.053 µ/h				$ge_{av.}$= 276.6	$gm_{av.}$=8.2

$ge_{av.}$ - average specific effective fuel consumption;

$gm_{av.}$ - average specific effective burning oil consumption.

The physico-chemical and spectral analysis of the lubrication oil is presented in Tables 8 and 9.

Table 8

Results of Oil Physico-Chemical Analysis

Sample taking	Running time, h	Water content, %	Viscosity at 100 °C, mm²/c	Flash point, °C	ATBF, %	Ash, %	TBH, mg KOH/g
$M10G_2K$	0	отс.	10.5	208	0	1.15	6.02
	7	none	10.5	184	1.45	1.01	5.56
	14	none	10.6	178	1.55	0.90	5.50
	21	none	10.8	165	1.87	0.97	5.38
	28	none	10.6	168	1.80	1.08	5.42
	35	none	10.8	170	2,25	1.06	5.38
	42	none	11.0	168	2,88	1.12	5.41
	50	none	11.2	173	1.23	1.19	5.87

.

.

Table 9

Oil spectral analysis results

Sample taking	Running time h	Fe g/t	Pb g/t	Al g/t	Cu g/t	Cr g/t	Sn g/t	Si g/t
M10G2K	0	0.3	9.4	0.4	0.08	0.4	1.7	6.3
	7	82,0	6.8	3.5	5.2	1.8	15.6	8.1
	14	96.6	8.9	4.6	7.4	2,4	20.8	10.0
	21	120	10.1	7.2	10.9	3.3	22,8	11.5
	28	157	10.7	10.0	14.3	3.9	20.2	23.8
	35	117	9.8	7.5	12,3	3.4	13.1	10.4
	42	116	10.4	12,3	15.5	3.9	12,9	11.3
	50	122	10.4	10.0	17.7	3.9	11.1	12,3

The results of indicating the 1st engine cylinder at 92% load are presented in Table 10. the indication procedure is presented in Appendix 9.

The emission of engine exhaust gas at 92% load and after the first stage at various loads is presented in Tables 11. 12.

The engine vibration behavior at various loads after the first stage are presented in Table 13.

Table 10

Engine performance indicators at the first stage

Indicators	Running time, h						
	7	14	21	28	35	42	50
Ne, %	92.211	92.018	92.011	92.685	90.727	91.248	91.919
ηe	0.308	0.303	0.31	0.307	0.307	0.309	0.304
ηi	0.510	0.487	0.518	0.477	0.527	0.491	0.455
ηm	0.605	0.624	0.598	0.643	0.583	0.629	0.668
ge, g/kWh	277.1	279.4	274.6	277.1	276.9	275.4	279.4
Pi, kg/^{2}	6.698	7.289	6.489	7.432	7.74	7.259	6.836
Pz, kg/^{2}	63.56	63.01	62.46	63.4	64.22	63.34	63.48
ϕz, crank angle deg.	8.5	7.2	7.5	8.5	8	6.5	8
ϕia, crank angle deg.	-1	0	0	-1	-1	-1	-1
Pz, kg/cm^2	34.824	35.008	34.768	35.023	34.687	35.017	35.275
dp/dϕ_{av}, kg/sq.cm.deg.	3.243	3.264	3.663	3.033	3.297	3.772	3.214
dp/dϕ_{max}, kg/sq.cm.deg.	6.904	7.005	7.002	6.031	6.999	7.452	6.294
ϕmax, crank angle deg.	2.6	2.8	2.5	2.8	2.6	2.3	2.5
m	1.365	1.468	1.355	1.441	1.536	1.401	1.366
ϕm	2.5	2.5	2.5	2.5	2.5	2.5	2.5
xm	0.198	0.204	0.201	0.161	0.176	0.216	0.202
(dx/d⟩)max,	0.1	0.091	0.11	0.083	0.089	0.109	0.1
φ_{kg}	66.5	66.8	65.5	68.5	69	67.5	69
$\phi_{1/2}$	14	14	13	15	16.5	14	13.5

Table 11

Engine exhaust gas emission at the first stage

Indicators	Running time, h						
	7	14	21	28	35	42	50
CO, %	0.128	0.129	0.123	0.137	0.130	0.126	0.122
CH, %	0.010	0.008	0.007	0.007	0.008	0.010	0.005

Table 12

Engine exhaust gas emission after the first stage

Ne, %	39 %	53 %	75 %	92 %
CO, %	0.291	0.267	0.226	0.122
CH, %	0.001	0.001	0.004	0.005
Gas temp., °C	241	280	340	357

Table 13

Engine vibration behavior after the first stage

Ne, %	39 %		53 %		75 %		92 %	
Frequency range, Hz	Vibration level, dB							
	99.5		99.5		101.9		101.0	
	f	A	f	A	f	A	f	A
500	450	677	450	684	450	982	450	602
1000	650	495	550	614	550	859	625	586
1500	1150	365	1175	404	1150	545	1025	455
2000	1850	323	1950	316	1875	270	1875	253
2500	2375	244	2050	303	2375	266	2425	241
3000	2775	238	2550	278	2900	287	2775	245
3500	3325	241	3400	230	3150	307	3375	243
4000	3975	218	3550	174	3775	229	3975	227
4500	4025	198	4100	180	4125	243	4050	216
5000	4800	193	4825	212	4825	193	4725	208
5500	5250	164	5225	169	5375	209	5175	164
6000	5800	170	5575	163	5700	202	5950	153
6500	6075	152	6075	131	6475	191	6300	190
7000	6900	123	6850	122	6525	189	6550	186
7500	7475	143	7200	111	7075	183	7350	162
8000	7525	124	7675	103	7975	156	7675	110
8500	8025	124	8225	105	8025	160	8425	119
9000	8975	114	8775	113	8700	146	8800	108
9500	9500	107	9225	113	9050	114	9250	137
10000	9850	106	9950	116	9950	131	9750	117

Upon completion of the first work stage, the engine was disassembled and measured in conformity with the Clause 1.2 of the test program. The measurement results are presented in Appendices 1 - 4 and in Figures 6-8.

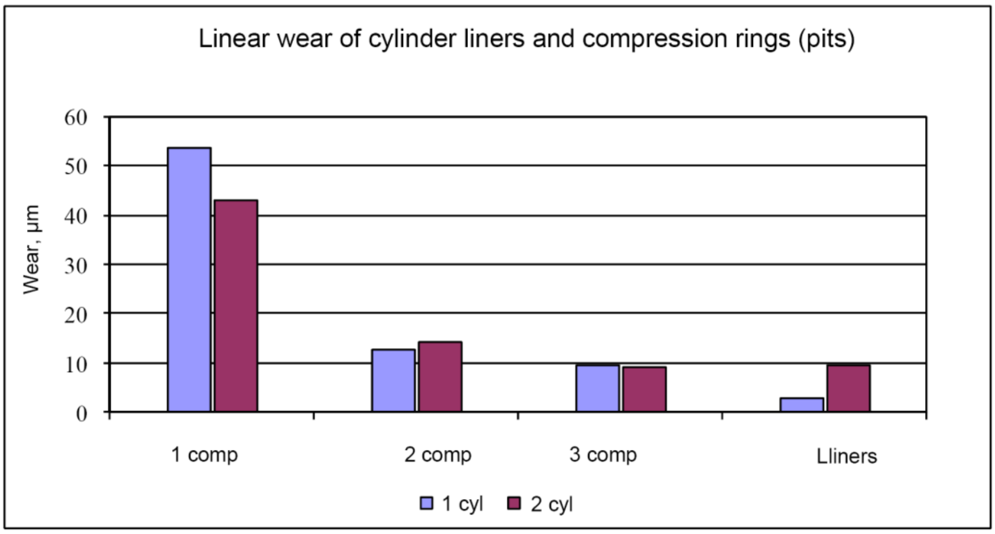


Figure 6

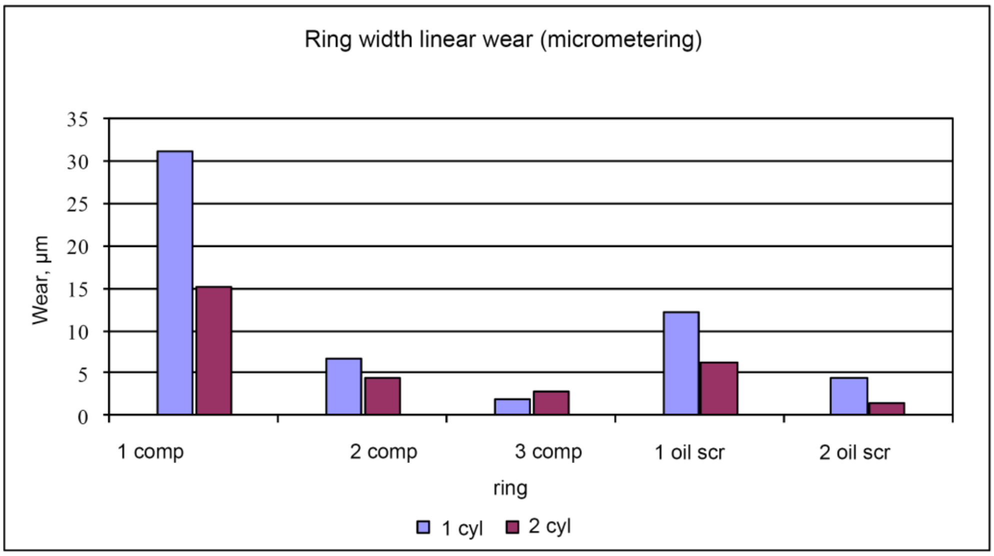


Figure 7

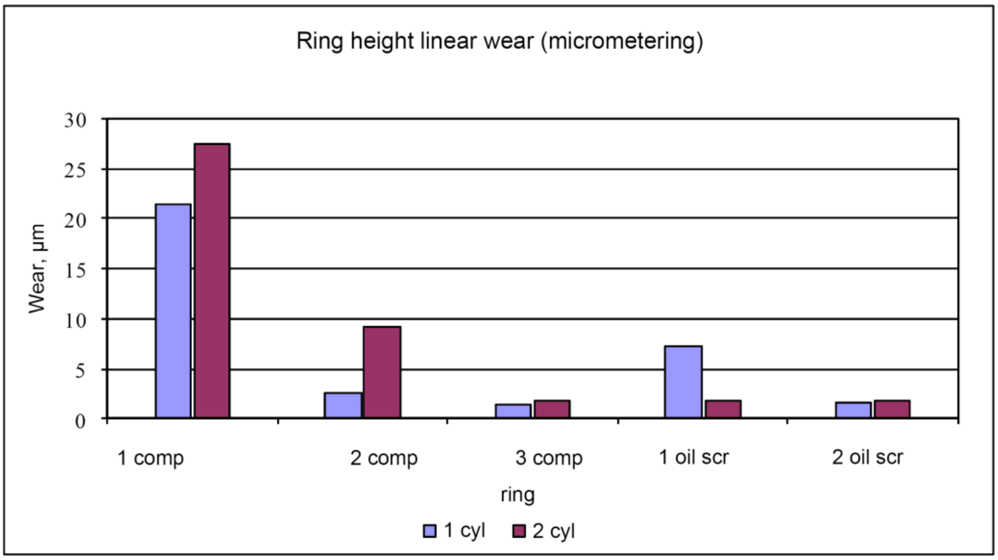


Figure 8

2 EXPERIMENTAL STUDIES OF A 2TCh8.5/11 ENGINE RUNNING ON LUBRICATION OIL WITH SUPROTEC TRIBOTECHNICAL COMPOUND

The second stage of the tests: engine running on lubrication oil with SUPROTEC tribotechnical compound is presented in Table 14.

Table 14

Engine running on lubrication oil with 0.2% SUPROTEC

Running time h	Power, kW	Wear 1 W μm	Exhaust gas temperature °C	Spec. eff. fuel consumption g/(kWh)	Spec. eff. oil consumption g/(kWh)
57	7.21	0.04	426	286.9	6.3
64	7.21	0.62	412	280.5	6.9
71	6.98	0.01	422	288.1	7.3
78	6.98	0.30	422	289.7	8.6
85	7.12	0.37	410	288.7	7.2
92	7.10	0.62	384	278.7	7.7
100	7.28	0.86	374	276.2	6.3
Average wear rate Vav= 0.053 μ/h				$g_{e\,av.}$= 285.4	$g_{m\,av.}$=7.2

The physico-chemical and spectral analysis of the lubrication oil is presented in Tables 15 and 16.

Table 15

Results of Oil Physico-Chemical Analysis

Sample taking	Running time, h	Water content, %	Viscosity at 100 °C, mm²/s	Flash point, °C	ATBF, %	Ash, %	TBH, mg KOH/g
M10G₂K +0.2 % SUPROTEC	50	none	11.2	173	1.23	1.19	5.87
	57	none	11.8	170	3.1	1.12	5.4
	64	none	13.9	176	2,3	1.15	5.59
	71	none	12,1	173	3.17	1.19	5.5
	78	none	11.8	173	2,8	1.18	5.5
	85	none	12,0	170	3.32	1.25	5.35
	92	none	12,1	168	2,7	1.19	5.4
	100	none	11.8	163	2,02	1.28	5.6

Table 16

Oil spectral analysis results

Sample taking	Running time, h	Fe g/t	Pb g/t	Al g/t	Cu g/t	Cr g/t	Sn g/t	Si g/t
M10G₂K +0.2 % SUPROTEC	50	122	10.4	10.0	17.7	3.9	11.1	12,3
	57	121	10.6	14.7	14.3	3.9	8.91	22,4
	64	117	10.4	13.3	13.3	3.87	7.16	33.6
	71	135	12,1	20.5	16.6	4.64	8.8	34.8
	78	84.7	11.0	10.1	10.0	3.25	5.0	12,0
	85	86	12,2	19.7	13.2	3.6	6.3	22,5
	92	78.8	11.5	18.2	14.5	3.2	5.2	21.0
	100	72,6	11.7	17.2	14.5	3.12	5.4	22,2

The results of indicating of the 1st engine cylinder at 92% load are presented in Table 17.

The emission of engine exhaust gas at 92% load and after the first stage at various loads is presented in Tables 18. 19.

The engine vibration behavior at various loads after the first stage are presented in Table 20.

Table 17

Engine performance indicators at the first stage

Indicators	Running time						
	57	64	71	78	85	92	100
Ne, %	92.685	92.685	89.73	89.73	91.583	91.919	92.59
ηe	0.297	0.304	0.296	0.294	0.294	0.303	0.305
ηi	0.406	0.474	0.324	0.471	0.359	0.402	0.399
ηm	0.73	0.64	0.911	0.624	0.818	0.753	0.764
ge, g/kWh	286.7	280.2	287.8	289.5	289.5	281.0	278.9
Pi, kg/^{2}	6.023	7.027	4.518	6.625	5.268	6.114	5.691
Pz, kg/^{2}	62.92	64.34	59.28	63.775	62.2	66.18	61.84
ϕz, crank angle deg.	7	7.5	6.5	6	6	6.5	8
ϕia, crank angle deg.	-1	-1	-1	0.5	0	-1	-1.5
Pz, kg/cm^2	35.159	35.323	35.416	35.611	35.842	35.701	35.864
$dp/d\phi_{av}$, kg/sq.cm.deg.	3.396	3.553	3.341	5.158	4.592	4.048	2.705
$dp/d\phi_{max}$, kg/sq.cm.deg.	7.243	7.513	6.41	8.377	8.698	8.303	5.5
ϕmax, crank angle deg.	2.6	2.1	1.7	2.7	2.2	2.6	3.1
m	1.314	1.402	1.21	1.314	1.242	1.027	1.103
ϕm	2	2	2	2.5	2	2.5	3
xm	0.159	0.196	0.277	0.191	0.22	0.238	0.225
$(dx/d\phi)max$,	0.105	0.107	0.131	0.115	0.161	0.155	0.1
φ_{kg}	69	69	67.5	70.5	70	69	56
φ_{t05}	13	14.5	11	13	12	8	7.5

Table 18

Engine exhaust gas emission at the second stage

Indicators	Running time, h						
	57	64	71	78	85	92	100
CO, %	0.188	0.137	0.180	0.159	0.170	0.119	0.112
CH, %	0.004	0.007	0.007	0.005	0.003	0.009	0.007

Table 19

Engine exhaust gas emission after the second stage

Ne, %	39 %	53 %	75 %	92 %
CO, %	0.133	0.122	0.123	0.119
CH, %	0.002	0.002	0.004	0.005
Gas temp., °C	228	235	305	374

Table 20

Engine vibration behavior after the second stage

Ne, %	39 %		53 %		75 %		92 %	
Frequency range, Hz	Vibration level, dB							
	86.5		90.1		99.1		100.6	
	f	A	f	A	f	A	f	A
500	450	823	450	909	375	574	325	525
1000	750	349	750	406	525	289	525	282
1500	1225	205	1225	274	1250	369	1175	251
2000	1525	193	1625	177	1825	309	1950	257
2500	2125	121	2050	153	2050	259	2050	215
3000	2925	72	2800	135	3000	226	2700	283
3500	3100	100	3175	108	3050	206	3100	241
4000	3925	58	4000	104	3600	157	3850	204
4500	4400	98	4075	113	4225	191	4100	214
5000	4725	207	4725	167	4900	546	4925	662
5500	5150	126	5250	119	5075	376	5025	411
6000	5975	169	5925	133	5975	264	5575	390
6500	6325	138	6025	158	6025	298	6125	274
7000	6725	152	6625	120	6775	227	6775	277
7500	7050	77	7500	51	7175	167	7275	206
8000	7625	48	7950	47	7525	88	7600	123
8500	8100	56	8300	45	8300	114	8325	115
9000	8725	40	8775	33	8525	110	8975	127
9500	9200	44	9150	42	9100	96	9050	104
10000	9775	60	9975	56	9900	118	10000	111

Upon completion of the second work stage, the engine was disassembled and measured in conformity with the Clause 1.2 of the test program. The measurement results are presented in Appendices 5 - 8 and in Figures 9-11.

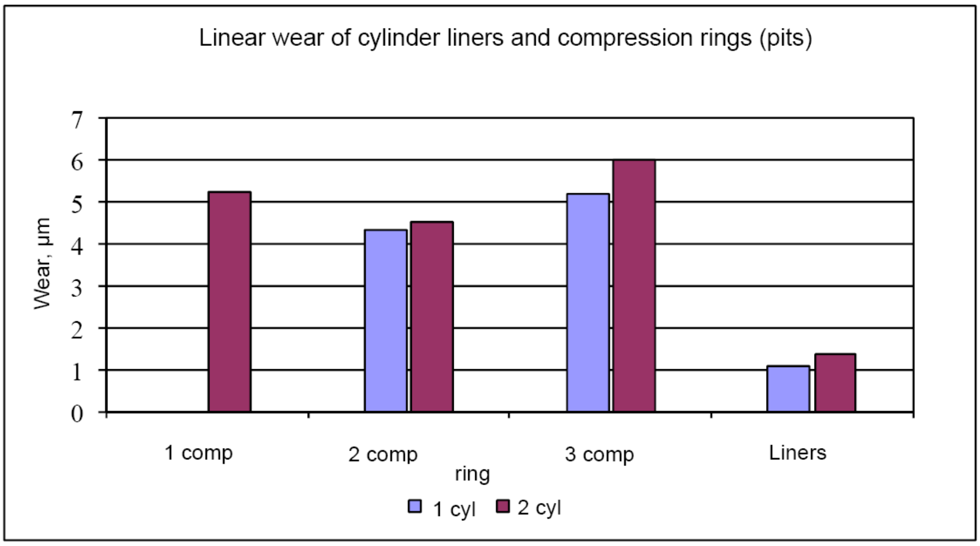


Figure 9

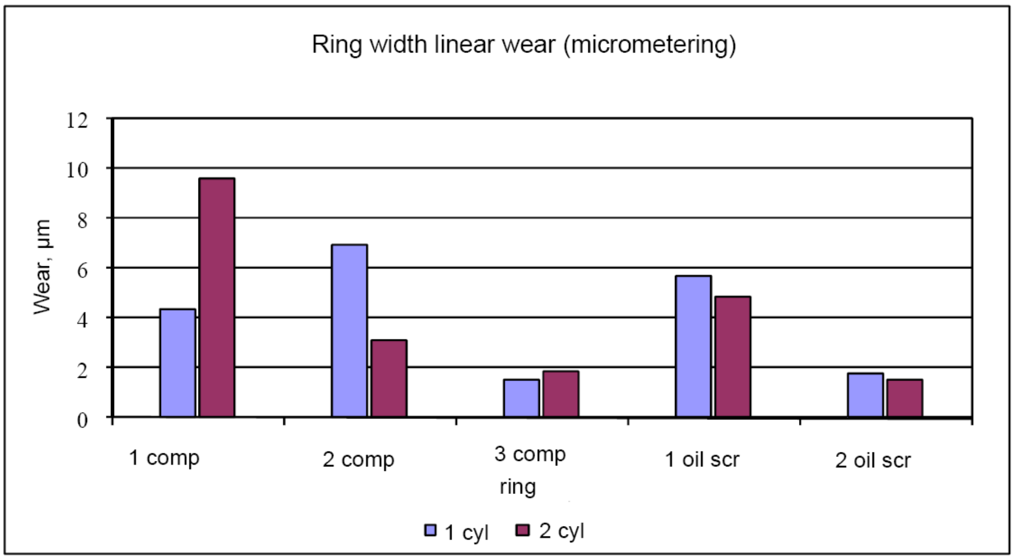


Figure 10

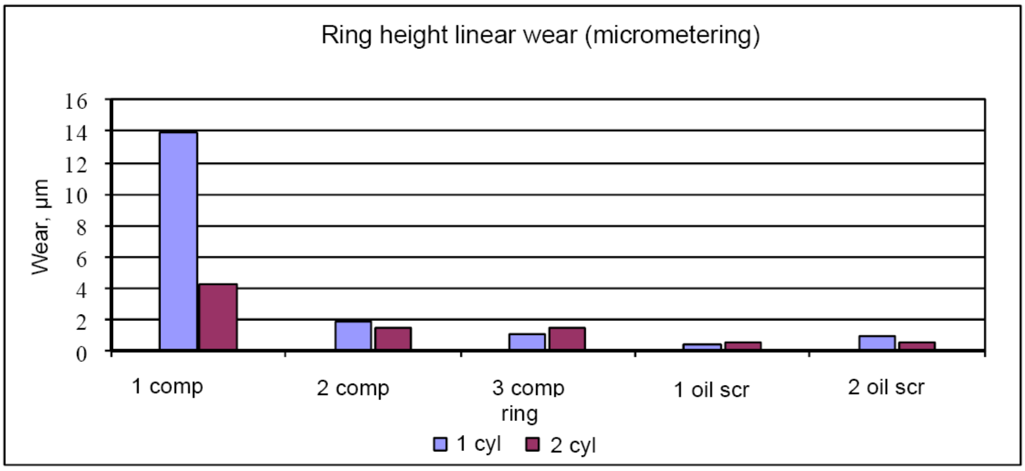


Figure 11

3. SUPROTEC TRIBOTECHNICAL COMPOUND EFFICIENCY ASSESSMENT BY ENGINE PERFORMANCE PARAMETERS

3.1 Comparative Analysis of Indicator, Effective, Economic, Lifetime and Environmental Parameters of an Engine

The calculation of the average effective, indicator and economical parameters of the engine (averaged by two cylinders) carried out, respectively, at the end of the first and the second engine running stages is presented in Table 21.

Table 21

Engine performance indicators

Indicators	Stage 1				Stage 2			
Ne, %	38.9	53.2	75.5	91.9	40.4	53.6	75.5	92,6
ηe	0.197	0.240	0.272	0.304	0.209	0.252	0.294	0.305
ηi	0.664	0.628	0.446	0.477	0.511	0.462	0.447	0.399
ηm	0.297	0.382	0.610	0.638	0.410	0.545	0.658	0.764
ge, g/kWh	431.7	354.6	312,5	279.4	406.3	337.2	288.9	278.9
Pi, kg/^{2}	6.2	6.6	4.2	6.8	4.7	4.0	5.4	5.7
Pz, kg/^{2}	64.2	64.5	59.3	63.5	62,7	60.9	63.3	61.8
φz, crank angle deg.	8.5	9.0	7.0	8.0	7.0	7.5	7.0	8.0
φia, crank angle deg.	-0.5	0.5	-1.5	-1.0	-1.0	-1.0	-1.0	-1.5
Pz, kg/cm^2	35.0	34.8	35.6	35.3	36.1	36.3	35.8	35.9
dp/d$φ_{av}$, kg/sq.cm.deg.	3.3	3.7	2,8	3.2	3.4	3.0	3.4	2,7
dp/d$φ_{max}$, kg/sq.cm.deg.	6.7	8.6	5.4	6.3	7.2	6.3	7.0	5.5
φmax, crank angle deg.	3.4	9.0	1.6	2,5	2,4	2,2	2,7	3.1
m	2,2	2,2	0.9	1.4	0.9	0.9	1.0	1.1
φm	2,5	3.5	2,0	2,5	2,0	2,0	2,5	3.0
xm	0.518	0.861	0.298	0.202	0.242	0.286	0.224	0.225
(dx/dφ)max,	0.390	0.573	0.126	0.100	0.161	0.184	0.129	0.100
$φ_{pg}$	64.5	70.5	62,5	69.0	53.0	49.0	54.0	56.0
$φ_{t05}$	2,0	2,5	5.5	13.5	5.0	4.5	6.0	7.5

For comparison ηe, ηi, ηm, ge at equal load Ne an approximation has been performed by regressional dependencies [9]:

$$ηe\ (ηi,\ ηm,\ ge)=b_0 + b_1{*}Ne + b_2{*}Ne^2, \quad (2)$$

The parameters of the regressional dependencies are presented in Tables 22 and 23.

Table 22

Regression statistics (stage 1)

Parameters	ηe	ηi	ηm	ge
Multiple R	0.9896	0.9084	0.9708	0.9671
R-square	0.9794	0.8252	0.9425	0.9354
Norm. R-square	0.9691	0.7378	0.6092	0.9031
Standard error	0.0080	0.0555	0.0403	20.4714
b_0	0.1284	0.8253	-	520.0967
b_1	0.0019	-0.0042	0.0074	-2,7052
t-statistics	9.57	8.91	-	15.21
	9.75	-3.07	24.90	-5.38

Table 23

Regression statistics (stage 2)

Parameters	ηe	ηi	ηm	ge
Multiple R	0.9999	0.9638	0.9905	0.9978
R-square	0.9998	0.9290	0.9811	0.9955
Norm. R-square	0.4997	0.8934	0.9717	0.9865
Standard error	0.0008	0.0151	0.0255	6.7455
b_0	-	0.5805	0.1688	723.8654
b_1	0.0066	-0.0019	0.0065	-10.3469
b_2	-	-	-	0.0600
t-statistics	265.28	22,57	3.87	14.58
	-	-5.11	10.20	-6.44
	-113.93	-	-	5.00

The results of the approximations are presented in Table 24 and in Figures 12 - 15.

Table 24

Approximation (Stage. 1).								
Ne, %	30	40	50	60	70	80	90	100
ηe1	0.186	0.205	0.225	0.244	0.263	0.282	0.302	0.321
ηi1	0.700	0.658	0.616	0.574	0.532	0.490	0.449	0.407
ηm1	0.221	0.295	0.369	0.443	0.517	0.591	0.664	0.738
ge1. g/kWh	438.9	411.9	384.8	357.8	330.7	303.7	276.6	249.6
Approximation (Stage. 2).								
Ne, %	30	40	50	60	70	80	90	100
ηe2	0.166	0.208	0.241	0.268	0.287	0.300	0.304	0.302
ηi2	0.523	0.504	0.485	0.465	0.446	0.427	0.408	0.388
ηm2	0.364	0.429	0.494	0.559	0.624	0.689	0.754	0.819
ge2, g/kWh	467.5	406.0	356.6	319.2	293.7	280.3	278.9	289.5

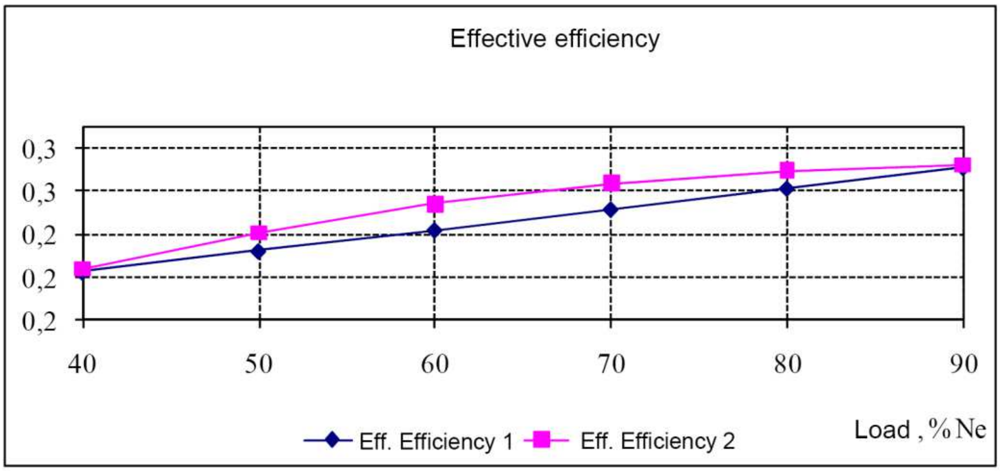


Figure 12

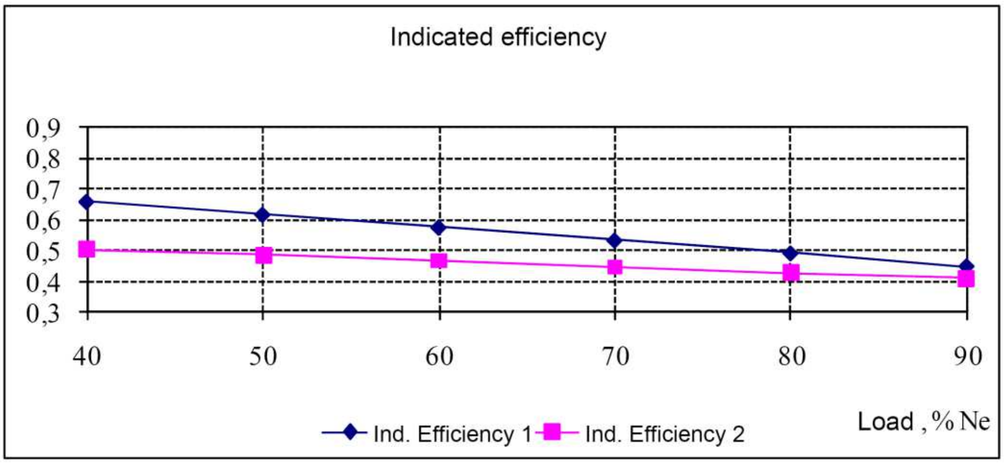


Figure 13

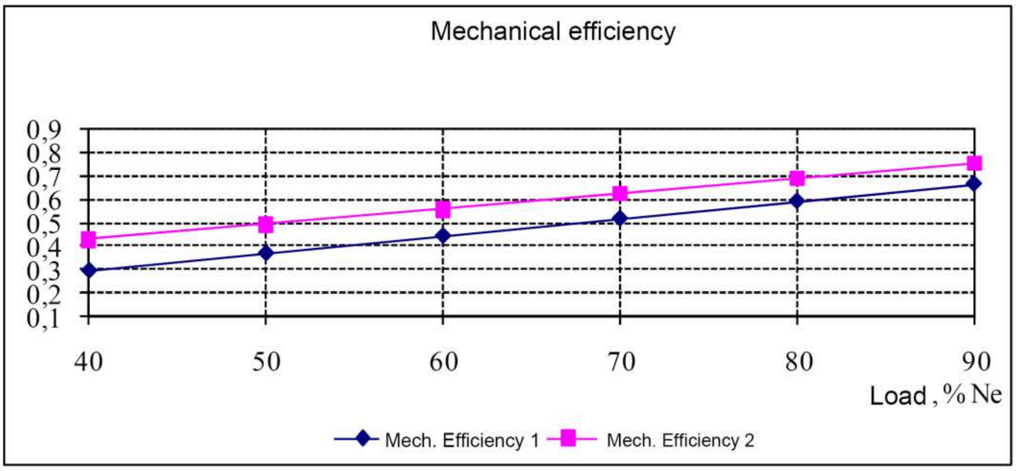


Figure 14

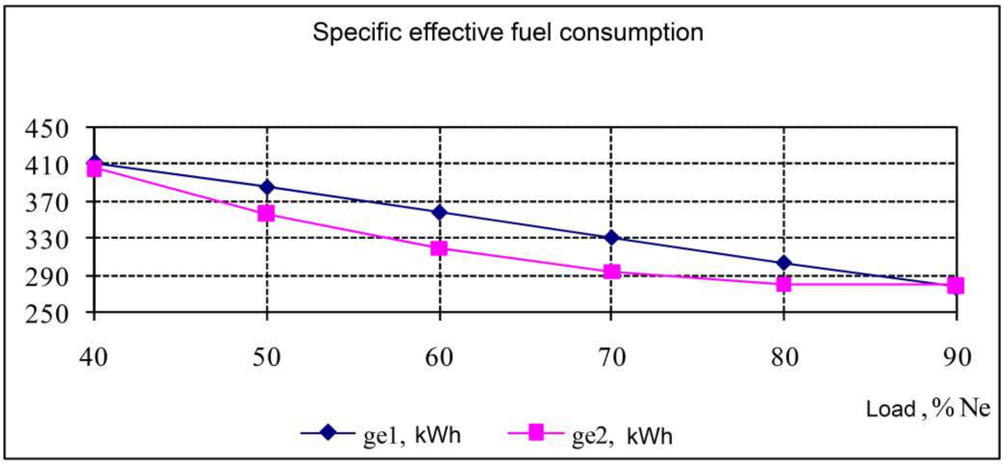


Figure 15

Dependencies between the principal effective and indicated engine performance indicators and the load when using standard lubrication oil correspond to the theoretical provisions and regularities of the work flow.

A decrease in indicated efficiency (Figure 13) is connected with the reduction of excess-air coefficient α for naturally aspirated engines as the injection rate increases. As a result, fuel combustion conditions deteriorate and $\eta_i$drops.

In case SUPROTEC is used, a drop in indicated efficiency is observed at low and medium loads. This is connected with a change in the conditions in heat transfer via the walls of cylinder liners.

An increase in mechanical efficiency is explained (Figure 14) by the fact that at constant engine rotation frequency n=const mechanical losses can be considered as constant Pm=const. Then as the average effective pressure Pe increases, relative loss value Pm/Pe decreases.

Using SUPROTEC brings about a change in the friction surfaces contact conditions and a decrease in friction resistance. As a result, mechanical efficiency increases by 15 - 45%; this corresponds to a 1.5 - 2.5 times decrease in friction losses.

The resulting characteristics (dependencies between the effective efficiency and the specific fuel consumption and the load are presented in Figures 12 and 15. It can be seen from dependencies η_e=f(Ne) и g_e=f(Ne) that at 50-80% loads using SUPROTEC brings about an increase in η_e and a decrease in g_e by 8-11%. As regards other loads, the effect is negligible. The dependency between the engine efficiency and running time is presented in Figure 16. The dynamics of increase in mechanical efficiency and reduction in indicated efficiency is evident.

Figure 16

SUPROTEC tribotechnical compound forms a modified layer increasing oil-retaining capacity a the friction surface. As a result, air charge loss decreases and compression pressure increases. This is confirmed by an indicator diagram record as fuel is cut off after the first and the second stages of the engine running presented in Figure 17.

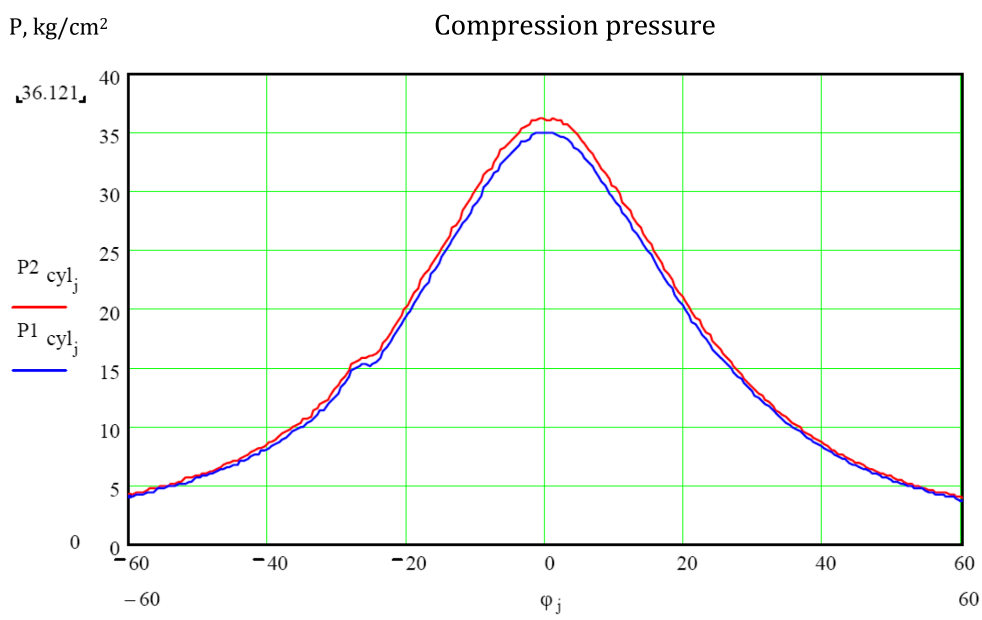


Figure 17

An increase in P_c bears witness to a decrease of air leaks during the compression stroke and, consequently, to an increase in air charge in a cylinder. As P_c increases, T_c increases as well. Therefore, self-ignition occurs earlier. This is attested to by an increase in ignition angle φ_{ig} before the top center. Fuel burns more rapidly (φ_{pg} decreases) and more evenly (the maximum combustion rate (dx/d))max decreases), bringing about a decrease in engine running severity (dp/d$)_{max}$), except power range close to the full power.

The dependency between compression pressure and the engine running time is shown in Figure 17. It is evidence that the presence of SUPROTEC tribotechnical compound brings about a gradual increase in compression pressure at various loads from 0.5 to 2.2 kg/cm^2 (Table 24).

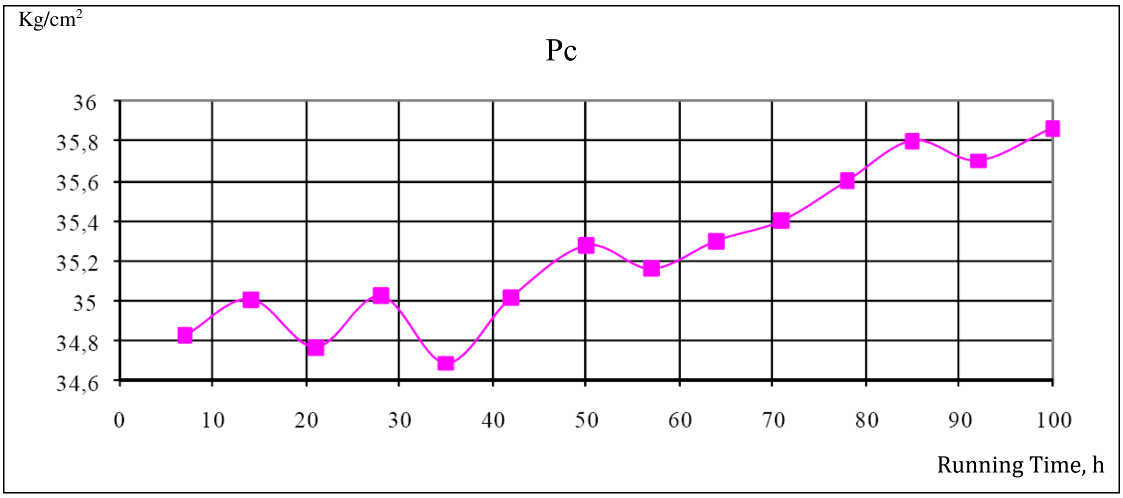


Figure 17

3.2 Comparative Analysis of Engine Lifetime Parameters

The comparative analysis of engine lifetime parameters is presented in Table 25.

As it can be seen from Table 25. using SUPROTEC tribotechnical compound brings about:

- a 5-6 times reduction in cylinder liners wear;
- a 1.5-6 times reduction in piston rings wear;
- a 20% reduction in connection rod bearing shells wear;
- a 3-4 times reduction in total ring and piston groove wear.

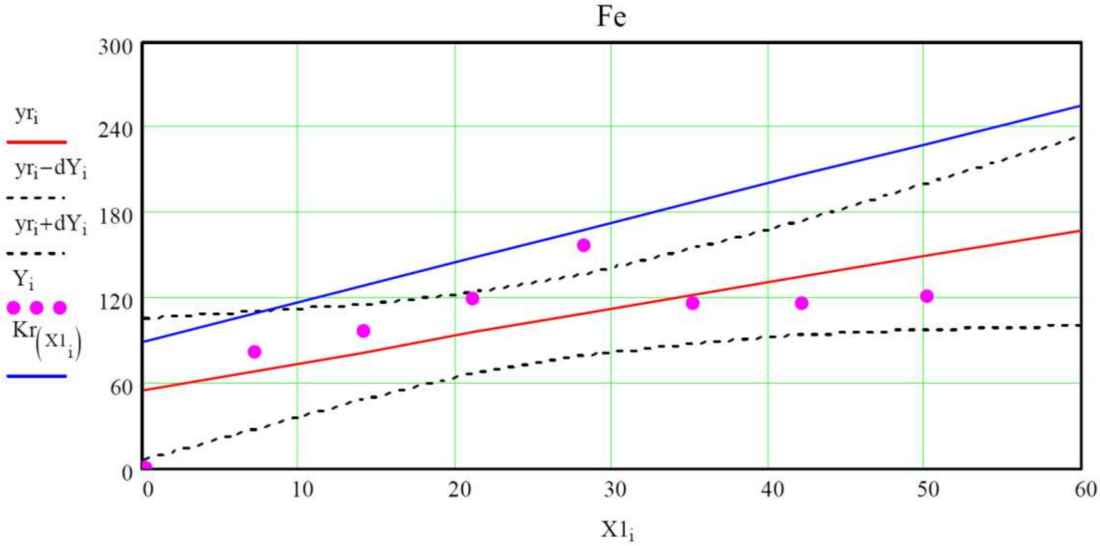
Table 25

Cylinder-piston group components	Measurement method	Stage 1 59 h on standard oil (av. wear)	Stage 1 50 h on oil with SUPROTEC (av. wear)	Wear ratio
Cylinder liners	Pits, μm	6.3	1.2	5.25
	ARAB, μm	2,7	0.5	5.40
Compression rings	Pits, μm	23.7	4.2	5.64
	Weighing, mg	76.0	44.7	1.70
Compression rings (width)	Micrometering, μm	10.3	4.6	2,24
Compression rings (height)	Micrometering, μm	10.7	4.0	2,68
Oil scraper rings	Weighing, mg	42,6	28.3	1.51
Oil scraper rings (width)	Micrometering, μm	6.1	4.1	1.49
Oil scraper rings (height)	Micrometering, μm	3.1	0.6	5.17
Connection rod bearing shells	Weighing, mg	3.4	2,8	1.21
Gaps between rings and piston grooves	Using a feeler gauge, μm	35	9	3.89
Ring joint gaps	Using a feeler gauge, μm	131	55	2,38

3.3. Spectral Analysis of Lubrication Oil

In order to explain the nature of changes in metal concentrations in lubrication oil (Tables 9. 16), it is necessary to calculate the dynamics of crankcase oil level, the actual burning oil consumption and the theoretical quantity of metal ingress in oil. The software presented in Appendix 10 is used for that.

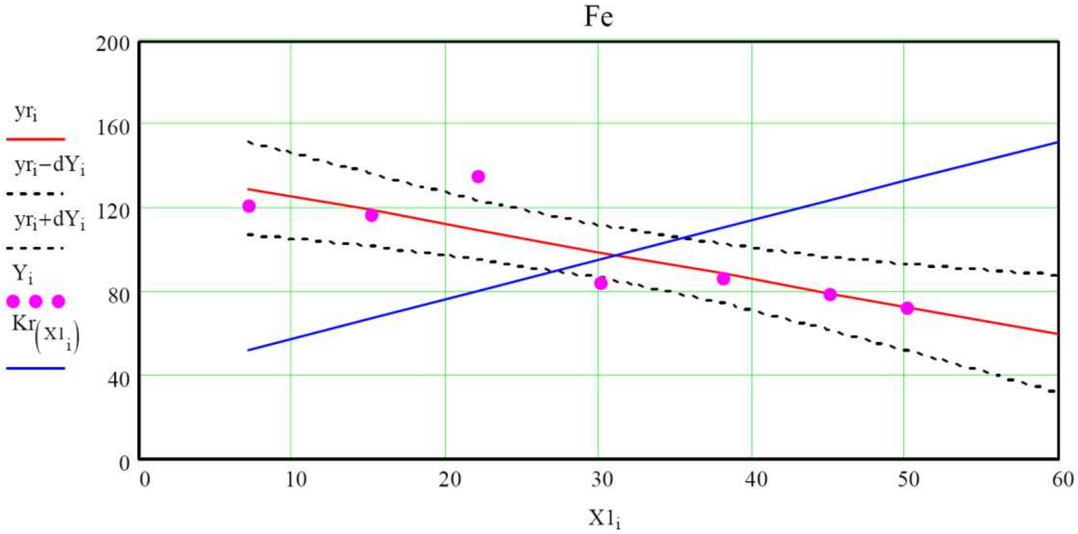
Comparison between calculated and actual iron concentrations in oil during the first stage of running demonstrates that the actual Fe ingress in rate is 1.5 times lower than the calculated one (Figure 18). At the second stage, Fe concentration even drops (Figure 19). This is connected with two processes: a sharp decrease in wear rate and sufficiently large burning oil consumption. Topping up fresh oil reduces concentration.



Actual Fe concentration change rate (g/t/h) $C_1 - 1.87$

Calculated Fe concentration change rate (g/t/h) $C2_1 - 2.772$

Figure 18



Actual Fe concentration change rate (g/t/h) $C_1 - 1.327$

Calculated Fe concentration change rate (g/t/h) $C2_1 - 1.887$

Figure 19

It is important to note that a decrease in wear rate recorded by concentrations of metals in lubrication oil occurred not only in cylinder-piston group components (Fe, Cr), but also in crank-shaft bearings and other parts (Cu, Pb, Sn). However, the concentration of Al remained rather high. It is evidence of piston wear. The concentration of Si at the beginning of the second stage increased and then began to decrease. This is a component of SUPROTEC tribotechnical compound.

3.4 Comparative Analysis of Environmental Parameters

The dependencies between exhaust gas emissions and running time and load are presented in Figures 20 and 21 (based on the data from Tables 11. 12, 18 and 19). It is evident that at the second stage of running with SUPROTEC the CH content decreases immediately, and the CO content, by the end of the stage. This bears evidence to an increase in fuel efficiency.

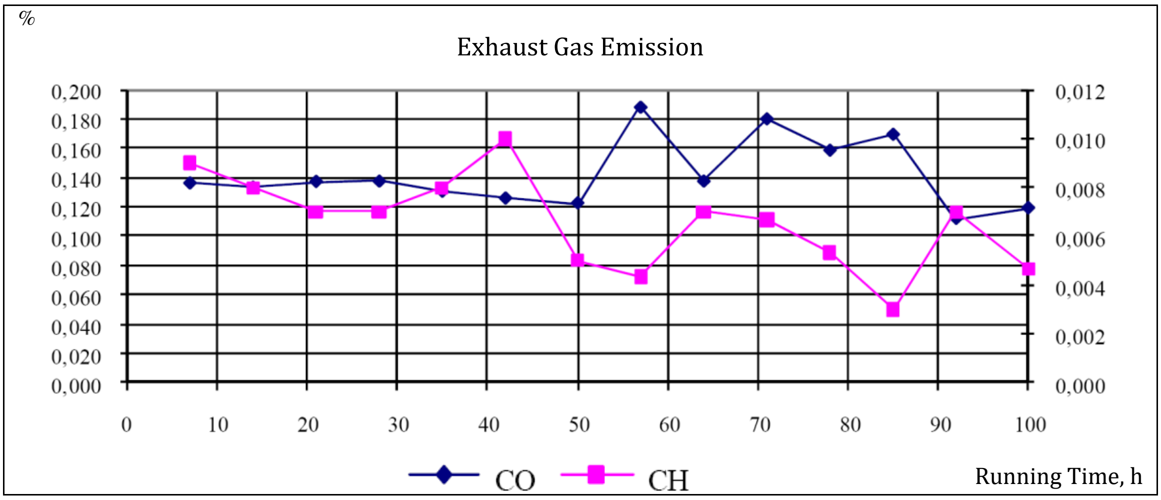


Figure 20

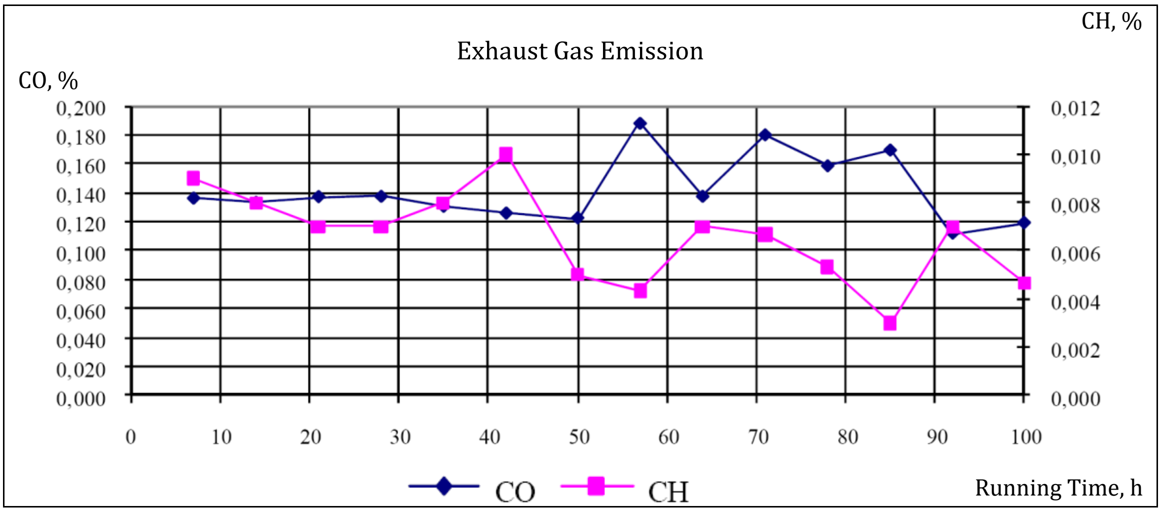


Figure 21

A comparative analysis of exhaust gas emission demonstrates close dependences on the load. However, CO concentration virtually does not depend on the load when running with SUPROTEC. Usually, an increase in CO at low loads is connected with a deterioration of air/fuel mixing conditions at low injection rates, low cycle temperature and low combustion chamber temperature. Using SUPROTEC neutralized these shortcomings (see Cl. 3.1.).

An analysis of vibration behavior (based on the data from Tables 13 and 20) demonstrates that the total vibration level at the end of the second stage (50 hours running with SUPROTEC) decreases especially noticeably at low and medium loads (figure 22).

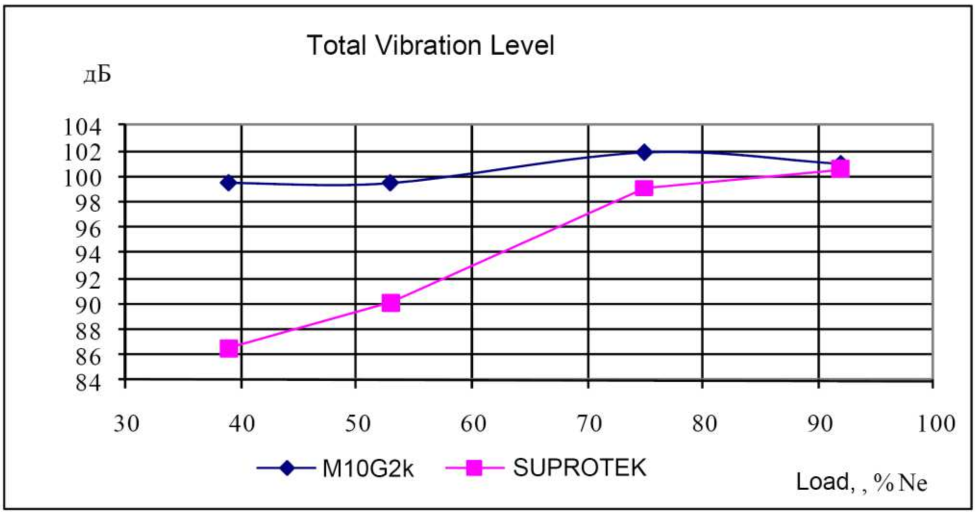


Figure 22

A spectral analysis of power density (Figures 23-26) shows that at 75-92% Ne loads at the end of the first stage low-frequency spectral vibration power density (up to 1500 Hz) dominates, and at the end of the second stage, the high-frequency one (5-8 kHz) dominates.

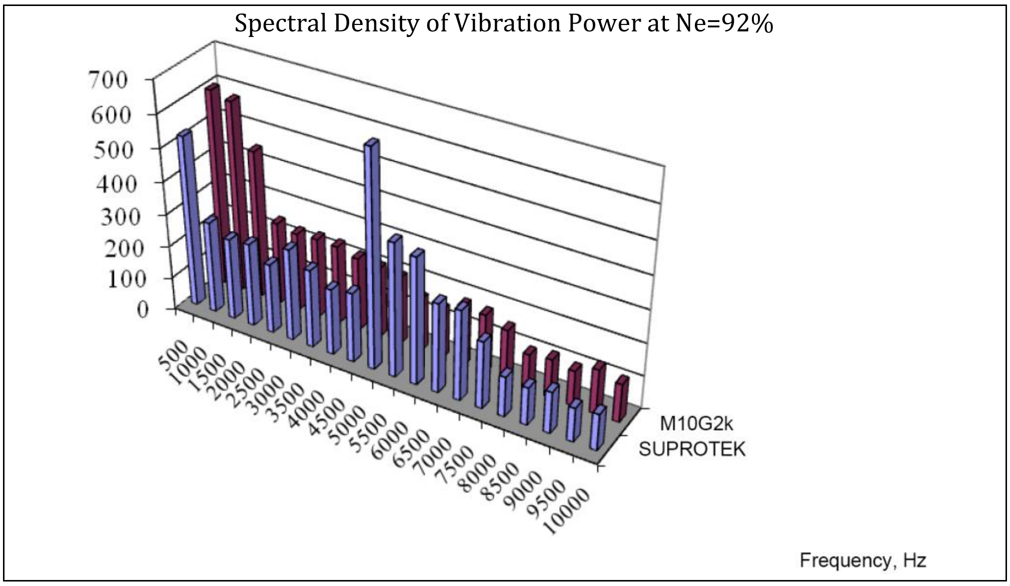


Figure 23

Low frequencies correspond to metal on metal impacts and partially, to the diesel engine cycle. 5-8 kHz frequencies correspond to cavitation and vortex processes of liquid and gas flowing. Therefore, SUPROTEC damped impacts and caused an acceleration in liquid or gas flow rates.

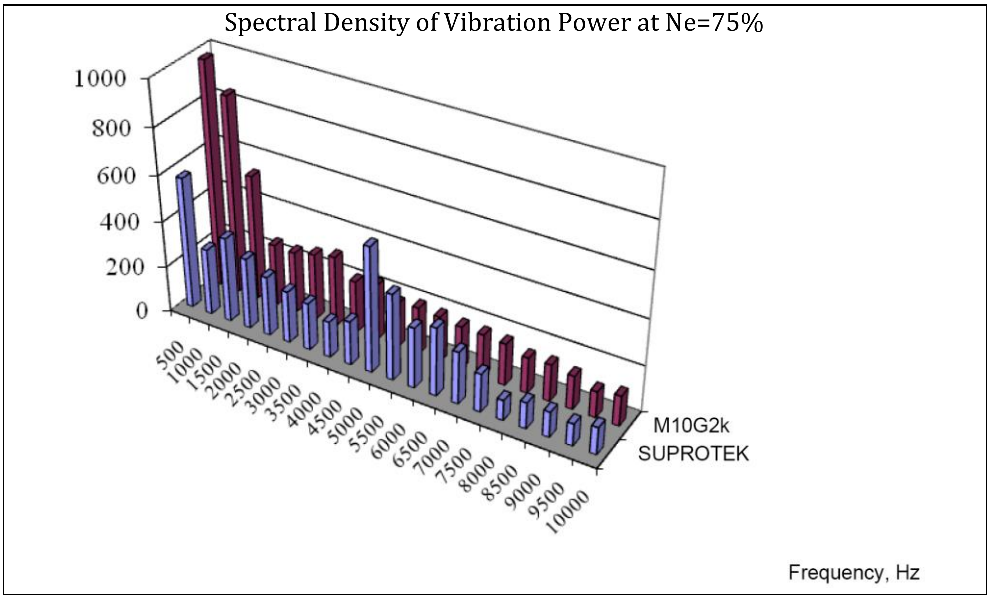


Figure 24

At 39-53% Ne loads at the end of the second stage, vibration power decreases virtually at all frequencies (except 0 - 500 Hz frequencies)

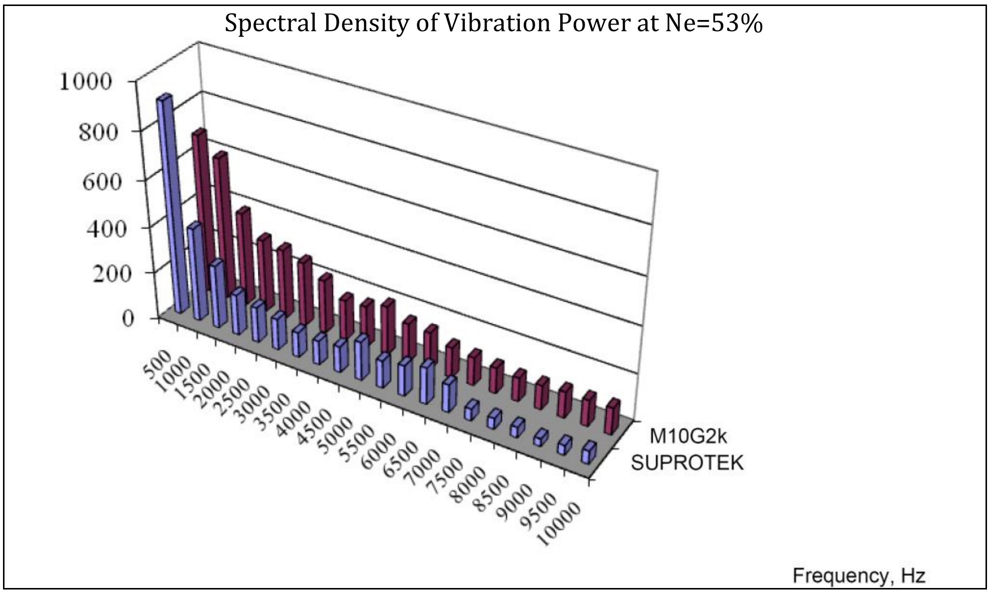


Figure 25

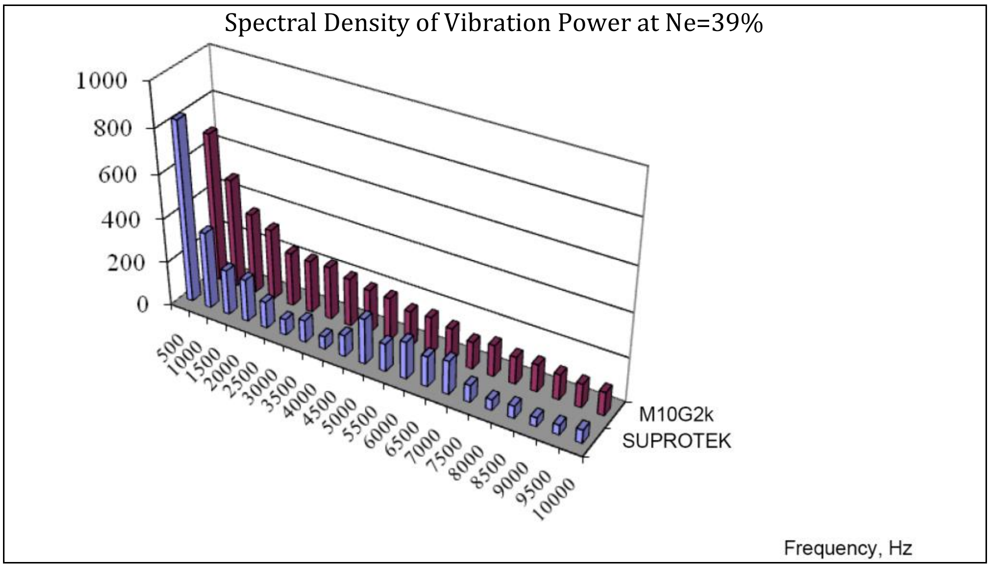


Figure 26

Therefore, it can be concluded that using SUPROTEC brings about an average 6 dB decrease in total vibration level. The greatest decrease is observed at low loads, at the high ones, spectral power peaks move into the high-frequency range.

CONCLUSION

1. A layer modified according to the SUPROTEC technology protects a friction surface in case of emergency loss of lubricant for a period of time that is sufficient to detect such a breakdown, although wear increases sharply in this case. As compared to a friction unit running under normal conditions (with a lubricant), wear increases 4-5 times, but in absolute values such a wear reduces the friction unit service life by fractions of percents.
2. Adding SUPROTEC tribotechnical compound to M12G2K oil brings about a 40% increase of the maximum load causing scoring as compared to "clean" M12G2K. This allows to create normal friction conditions for critical units without changing the type of lubrication oil.
3. The tribotechnical compound is an antifriction additive as well. A significant reduction in friction losses bring about a 15-45% increase in mechanical efficiency ηm of the 2TCh 8.5/11 engine.
4. The tribotechnical compound is an antiwear additive. A 5-6 time increase in the diesel cylinder liners wear rate corresponds to the same increase in their useful life. A 1.5-2 times decrease in piston rings wear rate allows to prolong the period between repairs correspondingly.
5. A decrease in maximum combustion pressure, maximum pressure increase rate and the formation of a damping quazi-fluidized layer when an engine runs with a tribotechnical compound brings about a substantial decrease in vibrations level, bearing witness to an increase in environmental friendliness and a decrease in engine parts breakdown probability.

6. Using SUPROTEC at 50-80% loads brings about an 8-11% increase in effective efficiency (η_e) and the same decrease in effective fuel consumption (g_e). In the other load ranges, the effect is negligible.
7. Physico-chemical analysis of oil demonstrate that adding the tribotechnical compound does not deteriorate the lubrication oil characteristics as regards the base package of additives.
8. The tribotechnical compound influences the engine cycle because an antifriction coating with a great oil-retaining capacity is created, the compression pressure is increased and causes a decrease in running "rigidity" (dP/dφ) and a decrease in maximum combustion pressure Pz, doubtlessly causing an increase in engine durability and reliability.
9. It is necessary to carry out long-term field tests (up to 1000 h) or perform a periodical control of actual facilities in order to determine the frequency of adding tribotechnical compound to lubrication oil.

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Appendix 1

DIESEL MEASUREMENT AFTER THE FIRST STAGE (29.09.03)

Ring to Piston Groove Gap (mm)

Cylinder 1	before stage	after stage	Wear	Cylinder 2	before stage	after stage	Wear
Comp. ring 1	0.1	0.23	0.13	Comp. ring 1	0.135	0.26	0.125
Comp. ring 2	0.12	0.13	0.01	Comp. ring 2	0.135	0.16	0.025
Comp. ring 3	0.1	0.12	0.02	Comp. ring 3	0.14	0.14	0
Oil scr. ring 1	0.08	0.09	0.01	Oil scr. ring 1	0.09	0.1	0.01
Oil scr. ring 2	0.08	0.09	0.01	Oil scr. ring 2	0.08	0.09	0.01
Average wear (mm)			0.036	Average wear (mm)			0.034
Average wear broken down by cylinders (mm)							0.035

Ring Joint Gap (mm)

Cylinder 1	before stage	after stage	Wear	Cylinder 2	before stage	after stage	Wear
Comp. ring 1	0.4	0.5	0.1	Comp. ring 1	0.6	0.85	0.25
Comp. ring 2	0.6	0.7	0.1	Comp. ring 2	0.55	0.75	0.2
Comp. ring 3	0.8	0.85	0.05	Comp. ring 3	0.65	0.75	0.1
Oil scr. ring 1	1.1	1.35	0.25	Oil scr. ring 1	0.7	0.75	0.05
Oil scr. ring 2	1.15	1.16	0.01	Oil scr. ring 2	0.65	0.85	0.2
Average wear (mm)			0.102	Average wear (mm)			0.16
Average wear broken down by cylinders (mm)							0.131

Weighing Rings (mg)

Cylinder 1	before stage	after stage	Wear	Cylinder 2	before stage	after stage	Wear
Comp. ring 1	16.8750	16.7007	174.3	Comp. ring 1	17.2981	17.0916	206.5
Comp. ring 2	16.7820	16.7116	70.4	Comp. ring 2	16.8877	16.8255	62,2
Comp. ring 3	16.8202	16.8158	4.4	Comp. ring 3	16.8521	16.9138	-61.7
Oil scr. ring 1	19.4300	19.3878	42,2	Oil scr. ring 1	20.3134	20.2666	46.8
Oil scr. ring 2	18.8130	18.7675	45.5	Oil scr. ring 2	20.3241	20.2881	36.0
Average wear (mg)			67.4	Average wear (mg)			58.0
Average compression ring wear (mg)							76.0
Average oil scraper ring wear (mg)							42,6

Weighing Bearing Shells (mg)

Cylinder 1	before stage	after stage	Wear	Cylinder 2	before stage	after stage	Wear
Upper half	62,3876	62,3822	5.4	Upper half	61.4067	61.4026	4.1
Lower half	62,2993	62,2971	2,2	Lower half	62,0676	62,0658	1.8
Average wear (mg)			3.8	Average wear (mg)			2,9
Average wear broken down by cylinders (mg)							3.4

Determining Linear Wear of Cylinder Liners (Pits, mm)

Measurement No.	Cylinder 1		Wear	Measurement No.	Cylinder 2		Wear
	Measurement 1	Measurement 2			Measurement 1	Measurement 2	
1	110	101	4.30	1	90	75	7.16
2	105	100	2,39	2	96	79	8.12
3	99	98	0.48	3	104	78	12,42
4	99	85	6.69	4	100	83	8.12
5	91	85	2,87	5	85	50	16.72
6	89	80	4.30	6	96	76	9.55
7	100	94	2,87	7	89	75	6.69
8	98	98	0.00	8	84	68	7.64
Average cylinder 1 wear			2,98	Average cylinder 2 wear			9.55
Average wear broken down by cylinders (mg)							6.3

Determining Linear Wear by Compression Ring Width (Pits, mm)

Pit No.	Cylinder 1. compress. ring 1			Pit No.	Cylinder 2, compress. ring 1		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	90	0	64.16	1	90	0	64.16
2	77	0	54.89	2	90	57	23.53
3	63	0	44.91	3	85	36	34.93
4	72	0	51.33	4	71	32	27.80
5	67	0	47.76	5	91	33	41.35
6	82	0	58.46	6	78	39	27.80
7	77	0	54.89	7	115	0	81.98
Average compr. ring 1 wear			53.77	Average compr. ring 1 wear			43.08
Pit No.	Cylinder 1. compress. ring 2			Pit No.	Cylinder 2, compress. ring 2		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	59	35	17.11	1	65	51	9.98
2	75	60	10.69	2	56	47	6.42
3	90	64	18.54	3	68	59	6.42
4	65	42	16.40	4	70	40	21.39
5	65	60	3.56	5	43	20	16.40
6	68	59	6.42	6	61	55	4.28
7	85	62	16.40	7	48	0	34.22
Average compr. ring 2 wear			12,73	Average compr. ring 2 wear			14.16
Pit No.	Cylinder 1. compress. ring 3			Pit No.	Cylinder 2, compress. ring 3		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	83	57	18.54	1	42	0	29.94
2	77	76	0.71	2	40	40	0.00
3	71	56	10.69	3	53	46	4.99
4	76	60	11.41	4	88	80	5.70
5	30	14	11.41	5	43	32	7.84
6	58	53	3.56	6	66	58	5.70
7	71	56	10.69	7	66	54	8.55
Average compr. ring 3 wear			9.57	Average compr. ring 3 wear			8.96
Average cylinder 1 ring wear			25.36	Average cylinder 2 ring wear			22,07
Average wear broken down by cylinders (mg)							23.7

Determining Linear Wear by Ring Width (Micrometering, µm)

Measurement No.	Cylinder 1. compress. ring 1			Measurement No.	Cylinder 2, compress. ring 1		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	9348	8660	68.8	1	9798	9628	17.0
2	9287	9134	15.3	2	9452	9432	2,0
3	9173	8950	22,3	3	9152	9148	0.4
4	9062	8895	16.7	4	9092	8965	12,7
5	9335	9100	23.5	5	9158	9150	0.8
6	9312	9080	23.2	6	9174	9100	7.4
7	9272	8798	47.4	7	9118	8457	66.1
Average compr. ring 1 wear			31.0	Average compr. ring 1 wear			15.2
Measurement No.	Cylinder 1. compress. ring 2			Measurement No.	Cylinder 2, compress. ring 2		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	6715	6533	18.2	1	9196	9184	1.2
2	7096	7086	1.0	2	9295	9276	1.9
3	7099	7086	1.3	3	9222	9084	13.8
4	6872	6870	0.2	4	8851	8765	8.6
5	7262	7239	2,3	5	9158	9149	0.9
6	7054	7030	2,4	6	9462	9428	3.4
7	6673	6465	20.8	7	9027	9018	0.9
Average compr. ring 2 wear			6.6	Average compr. ring 2 wear			4.39
Measurement No.	Cylinder 1. compress. ring 3			Measurement No.	Cylinder 2, compress. ring 3		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	6721	6715	0.6	1	8990	8861	12,9
2	7242	7182	6.0	2	8896	8892	0.4
3	6951	6949	0.2	3	8900	8896	0.4
4	6918	6902	1.6	4	8844	8831	1.3
5	7014	7005	0.9	5	8823	8808	1.5
6	7167	7159	0.8	6	8894	8870	2,4
7	6752	6720	3.2	7	8998	8992	0.6
Average compr. ring 3 wear			1.9	Average compr. ring 3 wear			2,79
Average cylinder 1 ring wear			13.18	Average cylinder 2 ring wear			7.46
Average wear broken down by cylinders (mg)							10.3
Measurement No.	Cylinder 1. oil scrap. ring 1			Measurement No.	Cylinder 2, oil scrap. ring 1		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	8042	7958	8.4	1	9504	9348	15.6
2	8505	8182	32,3	2	9672	9666	0.6
3	8138	8095	4.3	3	9660	9662	-0.2
4	8443	8338	10.5	4	9638	9538	10.0
5	8217	8074	14.3	5	9538	9508	3.0
6	8380	8375	0.5	6	9553	9508	4.5
7	8137	7987	15.0	7	9619	9519	10.0
Average oil scr. ring 1 wear			12,19	Average oil scr. ring 1 wear			6.21
Measurement No.	Cylinder 1. oil scrap. ring 2			Measurement No.	Cylinder 2, oil scrap. ring 2		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	5401	5381	2	1	9536	9532	0.4
2	5711	5668	4.3	2	9640	9632	0.8
3	5365	5359	0.6	3	9508	9460	4.8
4	5589	5580	0.9	4	9588	9569	1.9
5	5366	5340	2,6	5	9580	9575	0.5
6	5701	5630	7.1	6	9540	9529	1.1
7	5412	5271	14.1	7	9530	9529	0.1
Average oil scr. ring 2 wear			4.51	Average oil scr. ring 2 wear			1.37
Average cylinder 1 oil scr. ring wear			8.35	Average cylinder 2 oil scr. ring wear			3.79
Average wear broken down by cylinders (µm)							6.1
Average cylinder 1 ring wear			10.76	Average cylinder 2 ring wear			5.63

Determining Linear Wear by Ring Height (Micrometering, µm)

Measurement No.	Cylinder 1. compress. ring 1			Measurement No.	Cylinder 2, compress. ring 1		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	4992	4758	23.4	1	5132	4782	35.0
2	4965	4735	23.0	2	5000	4788	21.2
3	4900	4750	15.0	3	4998	4785	21.3
4	4948	4760	18.8	4	5039	4755	28.4
5	4993	4760	23.3	5	5038	4748	29.0
6	4978	4777	20.1	6	5049	4790	25.9
7	5058	4787	27.1	7	5131	4818	31.3
Average compr. ring 1 wear			21.53	Average compr. ring 1 wear			27.44
Measurement No.	Cylinder 1. compress. ring 2			Measurement No.	Cylinder 2, compress. ring 2		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	4672	4652	2,0	1	4728	4551	17.7
2	4683	4652	3.1	2	4645	4547	9.8
3	4668	4652	1.6	3	4499	4429	7.0
4	4750	4682	6.8	4	4530	4445	8.5
5	4695	4639	5.6	5	4608	4515	9.3
6	4650	4653	-0.3	6	4600	4550	5.0
7	4665	4665	0.0	7	4598	4524	7.4
Average compr. ring 0.2 wear			2,69	Average compr. ring 2 wear			9.24
Measurement No.	Cylinder 1. compress. ring 3			Measurement No.	Cylinder 2, compress. ring 3		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	4811	4800	1.1	1	4618	4601	1.7
2	4813	4770	4.3	2	4587	4574	1.3
3	4780	4770	1.0	3	4596	4588	0.8
4	4787	4777	1.0	4	4624	4615	0.9
5	4798	4790	0.8	5	4687	4678	0.9
6	4798	4790	0.8	6	4665	4650	1.5
7	4812	4809	0.3	7	4701	4645	5.6
Average compr. ring 3 wear			1.33	Average compr. ring 3 wear			1.81
Average cylinder 1 ring wear			8.51	Average cylinder 2 ring wear			12,83
Average wear broken down by cylinders (µm)							10.7

Appendix 4

Determining Linear Wear by Ring Height (Oil Scraper Rings)

Measurement No.	Cylinder 1. oil scrap. ring 1			Measurement No.	Cylinder 2, oil scrap. ring 1		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	9792	9758	3.4	1	9811	9780	3.1
2	9588	9544	4.4	2	9821	9810	1.1
3	9704	9580	12,4	3	9786	9778	0.8
4	9755	9649	10.6	4	9781	9778	0.3
5	9738	9660	7.8	5	9731	9678	5.3
6	9718	9660	5.8	6	9764	9751	1.3
7	9818	9760	5.8	7	9791	9785	0.6
Average oil scr. ring 1 wear			7.17	Average oil scr. ring 1 wear			1.79
Measurement No.	Cylinder 1. oil scrap. ring 2			Measurement No.	Cylinder 2, oil scrap. ring 2		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	9654	9611	4.3	1	9851	9840	1.1
2	9498	9485	1.3	2	9808	9768	4.0
3	9581	9565	1.6	3	9721	9711	1.0
4	9551	9533	1.8	4	9805	9792	1.3
5	9571	9565	0.6	5	9845	9821	2,4
6	9578	9569	0.9	6	9825	9802	2,3
7	9631	9626	0.5	7	9841	9832	0.9
Average oil scr. ring 2 wear			1.57	Average oil scr. ring 2 wear			1.86
Average cylinder 1 oil scr. ring wear			4.37	Average cylinder 2 oil scr. ring wear			1.82
Average wear broken down by cylinders (µm)							3.1
Average cylinder 1 ring wear			6.44	Average cylinder 2 ring wear			7.33

Appendix 5

DIESEL MEASUREMENT AFTER THE SECOND STAGE (18.10.03)

Ring to Piston Groove Gap (mm)

Cylinder 1	before stage	after stage	Wear	Cylinder 2	before stage	after stage	Wear
Comp. ring 1	0.23	0.29	0.06	Comp. ring 1	0.26	0.26	0
Comp. ring 2	0.13	0.13	0	Comp. ring 2	0.16	0.16	0
Comp. ring 3	0.12	0.13	0.01	Comp. ring 3	0.14	0.14	0
Oil scr. ring 1	0.09	0.1	0.01	Oil scr. ring 1	0.1	0.1	0
Oil scr. ring 2	0.09	0.1	0.01	Oil scr. ring 2	0.09	0.09	0
Average wear (mm)			0.018	Average wear (mm)			0
Average wear broken down by cylinders (mm)							0.009

Ring Joint Gap (mm)

Cylinder 1	before stage	after stage	Wear	Cylinder 2	before stage	after stage	Wear
Comp. ring 1	0.5	0.55	0.05	Comp. ring 1	0.85	1	0.15
Comp. ring 2	0.7	0.8	0.1	Comp. ring 2	0.75	0.8	0.05
Comp. ring 3	0.85	0.85	0	Comp. ring 3	0.75	0.8	0.05
Oil scr. ring 1	1.35	1.38	0.03	Oil scr. ring 1	0.75	0.8	0.05
Oil scr. ring 2	1.16	1.18	0.02	Oil scr. ring 2	0.85	0.9	0.05
Average wear (mm)			0.04	Average wear (mm)			0.07
Average wear broken down by cylinders (mm)							0.055

Weighing Rings (mg)

Cylinder 1	before stage	after stage	Wear	Cylinder 2	before stage	after stage	Wear
Comp. ring 1	16.7007	16.6138	86.9	Comp. ring 1	17.0916	17.0189	72,7
Comp. ring 2	16.7116	16.672	39.6	Comp. ring 2	16.8255	16.8103	15.2
Comp. ring 3	16.8158	16.7856	30.2	Comp. ring 3	16.9138	16.8901	23.7
Oil scr. ring 1	19.3878	19.3474	40.4	Oil scr. ring 1	20.2666	20.2386	28
Oil scr. ring 2	18.7675	18.7447	22,8	Oil scr. ring 2	20.2881	20.266	22,1
Average wear (mg)			43.98	Average wear (mg)			32,34
Average compression ring wear (mg)							44.7
Average oil scraper ring wear (mg)							28.3

Weighing Bearing Shells (mg)

Cylinder 1	before stage	after stage	Wear	Cylinder 2	before stage	after stage	Wear
Upper half	62,3822	62,3793	2,9	Upper half	61.4026	61.3989	3.7
Lower half	62,2971	62,2956	1.5	Lower half	62,0658	62,0628	3
Average wear (mg)			2,2	Average wear (mg)			3.35
Average wear broken down by cylinders (mg)							2,8

Determining Linear Wear of Cylinder Liners (Pits, mm)

Measurement No.	Cylinder 1		Wear	Measurement No.	Cylinder 2		Wear
	Measurement 1	Measurement 2			Measurement 1	Measurement 2	
1	101	100	1.0	1	75	74	0.7
2	100	100	0.0	2	79	77	1.5
3	98	96	1.8	3	78	78	0.0
4	85	85	0.0	4	83	79	3.1
5	85	83	1.6	5	50	48	0.9
6	80	79	0.8	6	76	74	1.4
7	94	92	1.8	7	75	73	1.4
8	98	96	1.8	8	68	65	1.9
Average cylinder 1 wear			1.1	Average cylinder 2 wear			1.4
Average wear broken down by cylinders (μm)							1.2

Determining Linear Wear by Compression Ring Width (Pits, mm)

Pit No.	Cylinder 1. compress. ring 1			Pit No.	Cylinder 2, compress. ring 1		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	0	0	0.0	1	0	0	0.0
2	0	0	0.0	2	57	43	8.2
3	0	0	0.0	3	36	0	7.5
4	0	0	0.0	4	32	0	6.0
5	0	0	0.0	5	33	0	6.3
6	0	0	0.0	6	39	0	8.9
7	0	0	0.0	7	0	0	0.0
Average compr. ring 1 wear			0.0	Average compr. ring 1 wear			5.3
Pit No.	Cylinder 1. compress. ring 2			Pit No.	Cylinder 2, compress. ring 2		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	35	0	7.1	1	51	0	15.1
2	60	55	3.3	2	47	42	2,6
3	64	60	2,9	3	59	52	4.5
4	42	39	1.4	4	40	22	6.5
5	60	55	3.3	5	20	0	2,3
6	59	50	5.7	6	55	54	0.6
7	62	52	6.6	7	0	0	0.0
Average compr. ring 2 wear			4.4	Average compr. ring 2 wear			4.5
Pit No.	Cylinder 1. compress. ring 3			Pit No.	Cylinder 2, compress. ring 3		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	57	38	10.5	1	0	0	0.0
2	76	71	4.3	2	40	0	9.3
3	56	50	3.7	3	46	28	7.8
4	60	56	2,7	4	80	71	7.9
5	14	0	1.1	5	32	0	6.0
6	53	44	5.1	6	58	50	5.0
7	56	40	8.9	7	54	43	6.2
Average compr. ring 3 wear			5.2	Average compr. ring 3 wear			6.0
Average cylinder 1 ring wear			3.2	Average cylinder 2 ring wear			5.3
Average wear broken down by cylinders (μm)							4.2

Determining Linear Wear by Ring Width (Micrometering, µm)

Measurement No.	Cylinder 1. compress. ring 1			Measurement No.	Cylinder 2, compress. ring 1		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	8660	8494	16.6	1	9628	9562	6.6
2	9134	9132	0.2	2	9432	9102	33
3	8950	8864	8.6	3	9148	9095	5.3
4	8895	8872	2,3	4	8965	8952	1.3
5	9100	9117	-1.7	5	9150	9122	2,8
6	9080	9027	5.3	6	9100	8939	16.1
7	8798	8802	-0.4	7	8457	8434	2,3
Average compr. ring 1 wear			4.4	Average compr. ring 1 wear			9.6
Measurement No.	Cylinder 1. compress. ring 2			Measurement No.	Cylinder 2, compress. ring 2		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	6533	6335	19.8	1	9184	9124	6
2	7086	7082	0.4	2	9276	9212	6.4
3	7086	7041	4.5	3	9084	9016	6.8
4	6870	6865	0.5	4	8765	8762	0.3
5	7239	7195	4.4	5	9149	9140	0.9
6	7030	7024	0.6	6	9428	9429	-0.1
7	6465	6282	18.3	7	9018	9002	1.6
Average compr. ring 2 wear			6.9	Average compr. ring 2 wear			3.1
Measurement No.	Cylinder 1. compress. ring 3			Measurement No.	Cylinder 2, compress. ring 3		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	6715	6712	0.3	1	8861	8812	4.9
2	7182	7180	0.2	2	8892	8885	0.7
3	6949	6935	1.4	3	8896	8899	-0.3
4	6902	6882	2	4	8831	8843	-1.2
5	7005	6966	3.9	5	8808	8727	8.1
6	7159	7138	2,1	6	8870	8868	0.2
7	6720	6710	1	7	8992	8983	0.9
Average compr. ring 3 wear			1.6	Average compr. ring 3 wear			1.9
Average cylinder 1 ring wear			4.3	Average cylinder 2 ring wear			4.9
Average wear broken down by cylinders (µm)							4.6
Measurement No.	Cylinder 1. oil scrap. ring 1			Measurement No.	Cylinder 2, oil scrap. ring 1		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	7958	7942	1.6	1	9348	9292	5.6
2	8182	8115	6.7	2	9666	9654	1.2
3	8095	8024	7.1	3	9662	9452	21
4	8338	8238	10	4	9538	9518	2
5	8074	8041	3.3	5	9508	9496	1.2
6	8375	8312	6.3	6	9508	9499	0.9
7	7987	7937	5	7	9519	9494	2,5
Average oil scr. ring 1 wear			5.7	Average oil scr. ring 1 wear			4.9
Measurement No.	Cylinder 1. oil scrap. ring 2			Measurement No.	Cylinder 2, oil scrap. ring 2		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	5381	5382	-0.1	1	9532	9507	2,5
2	5668	5650	1.8	2	9632	9590	4.2
3	5359	5338	2,1	3	9460	9475	-1.5
4	5580	5564	1.6	4	9569	9587	-1.8
5	5340	5320	2	5	9575	9522	5.3
6	5630	5612	1.8	6	9529	9522	0.7
7	5271	5238	3.3	7	9529	9513	1.6
Average oil scr. ring 2 wear			1.8	Average oil scr. ring 2 wear			1.6
Average cylinder 1 oil scr. ring wear			3.8	Average cylinder 2 oil scr. ring wear			3.2
Average wear broken down by cylinders (µm)							3.5
Average cylinder 1 ring wear			4.0	Average cylinder 2 ring wear			4.1

Determining Linear Wear by Ring Height (Micrometering, µm)

Measurement No.	Cylinder 1. compress. ring 1			Measurement No.	Cylinder 2, compress. ring 1		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	4758	4613	14.5	1	4782	4753	2,9
2	4735	4614	12,1	2	4788	4735	5.3
3	4750	4622	12,8	3	4785	4728	5.7
4	4760	4632	12,8	4	4755	4719	3.6
5	4760	4619	14.1	5	4748	4750	-0.2
6	4777	4616	16.1	6	4790	4716	7.4
7	4787	4636	15.1	7	4818	4763	5.5
Average compr. ring 1 wear			13.9	Average compr. ring 1 wear			4.3
Measurement No.	Cylinder 1. compress. ring 2			Measurement No.	Cylinder 2, compress. ring 2		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	4652	4573	7.9	1	4551	4565	-1.4
2	4652	4645	0.7	2	4547	4522	2,5
3	4652	4648	0.4	3	4429	4406	2,3
4	4682	4672	1	4	4445	4465	-2
5	4639	4628	1.1	5	4515	4498	1.7
6	4653	4644	0.9	6	4550	4536	1.4
7	4665	4652	1.3	7	4524	4465	5.9
Average compr. ring 1 wear			1.9	Average compr. ring 2 wear			1.5
Measurement No.	Cylinder 1. compress. ring 3			Measurement No.	Cylinder 2, compress. ring 3		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	4800	4783	1.7	1	4601	4536	6.5
2	4770	4768	0.2	2	4574	4572	0.2
3	4770	4768	0.2	3	4588	4564	2,4
4	4777	4758	1.9	4	4615	4612	0.3
5	4790	4782	0.8	5	4678	4680	-0.2
6	4790	4785	0.5	6	4650	4642	0.8
7	4809	4786	2,3	7	4645	4642	0.3
Average compr. ring 3 wear			1.1	Average compr. ring 3 wear			1.5
Average cylinder 1 ring wear			5.6	Average cylinder 2 ring wear			2,4
Average wear broken down by cylinders (µm)							4.0

Appendix 8

Determining Linear Wear by Ring Height (Oil Scraper Rings)

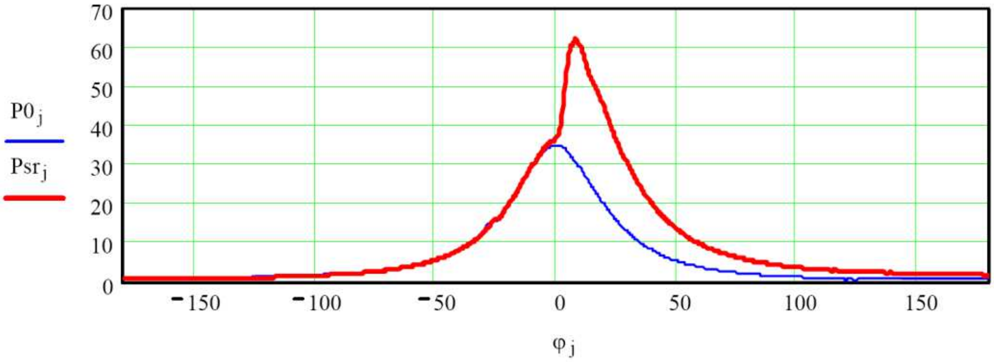
Measurement No.	Cylinder 1. oil scrap. ring 1			Measurement No.	Cylinder 2, oil scrap. ring 1		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	9758	9766	-0.8	1	9780	9762	1.8
2	9544	9531	1.3	2	9810	9813	-0.3
3	9580	9566	1.4	3	9778	9772	0.6
4	9649	9655	-0.6	4	9778	9772	0.6
5	9660	9644	1.6	5	9678	9670	0.8
6	9660	9652	0.8	6	9751	9743	0.8
7	9760	9764	-0.4	7	9785	9787	-0.2
Average oil scr. ring 1 wear			0.5	Average oil scr. ring 1 wear			0.6
Measurement No.	Cylinder 1. oil scrap. ring 2			Measurement No.	Cylinder 2, oil scrap. ring 2		
	Measurement 1	Measurement 2	Wear		Measurement 1	Measurement 2	Wear
1	9611	9599	1.2	1	9840	9832	0.8
2	9485	9482	0.3	2	9768	9762	0.6
3	9565	9535	3	3	9711	9712	-0.1
4	9533	9531	0.2	4	9792	9792	0
5	9565	9568	-0.3	5	9821	9811	1
6	9569	9562	0.7	6	9802	9795	0.7
7	9626	9611	1.5	7	9832	9822	1
Average oil scr. ring 2 wear			0.9	Average oil scr. ring 2 wear			0.6
Average cylinder 1 oil scr. ring wear			0.7	Average cylinder 2 oil scr. ring wear			0.6
Average wear broken down by cylinders (μm)							0.6
Average cylinder 1 ring wear			3.2	Average cylinder 2 ring wear			1.5

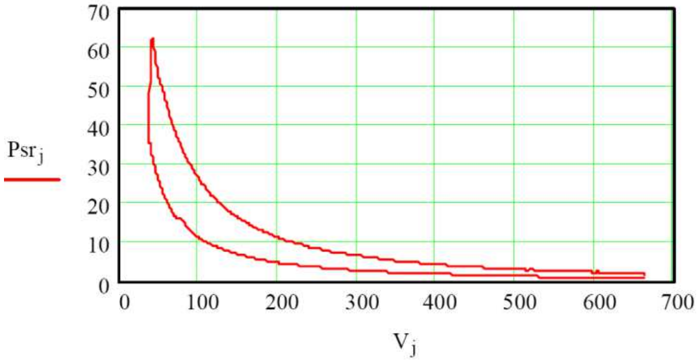
Appendix 9

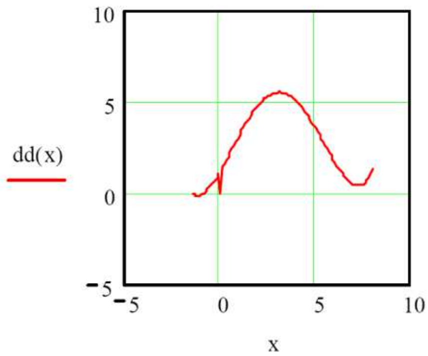
CALCULATION RESULTS:

After stage 2

Engine running conditions: Ne =92.6 % Nd = 1520 rpm







Indicated and effective engine parameters

$P_e = 4.35\ \frac{kg}{cm^2}$ $\eta_e = 0.305$ $\eta_m = 0.764$ $\eta_i = 0.399$ $P_c = 35.9$

$Pi = 5.7\ \frac{kg}{cm^2}$ $N_i = 11.992$ и.л.с. $g_e = 205.3$ г/(э.л.с.ч) $g_i = 0.157$

Adjustment parameters:

$Pz = 61.84\ \frac{kg}{cm^2}$ $\varphi Pz = 8$ Crank degree $\varphi_{ng} = -1.5$ (Combustion start)

$\lambda := \frac{Pz}{P_c}$ $\lambda = 1.724$

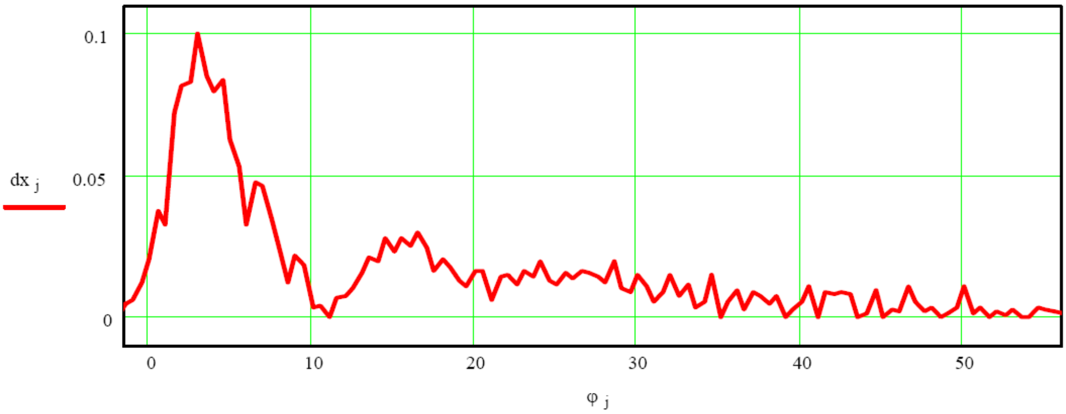
$dPmax = 5.5\ \frac{kg}{cm^2 \cdot grad}$ $\left(\frac{dP}{d\varphi}\right)_{max}$

$\varphi ddmax = 3.1$ (Crank angle corresponding to $\left(\frac{dP}{d\varphi}\right)_{max}$)

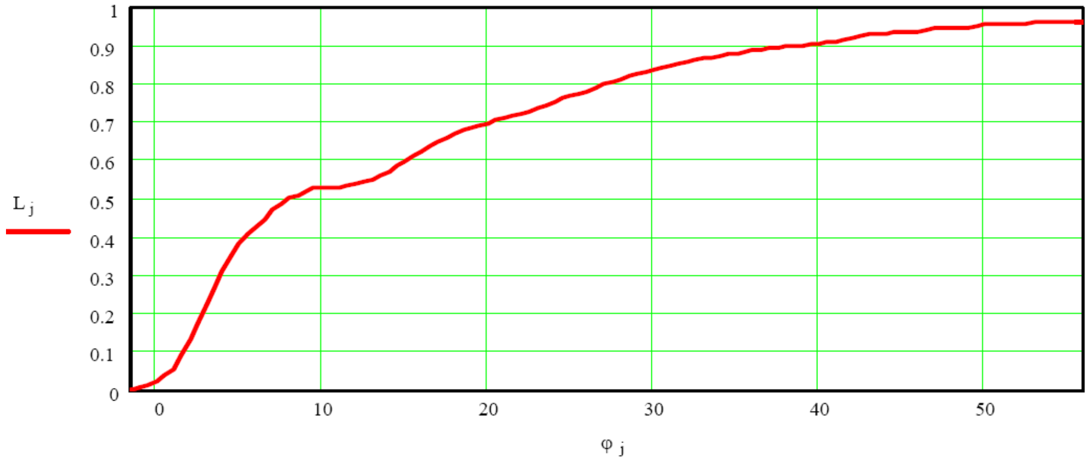
$dP_{cp} = 2.705$ (dPcp equal to $\left(\frac{dP}{d\varphi}\right)_{cp}$)

MAC

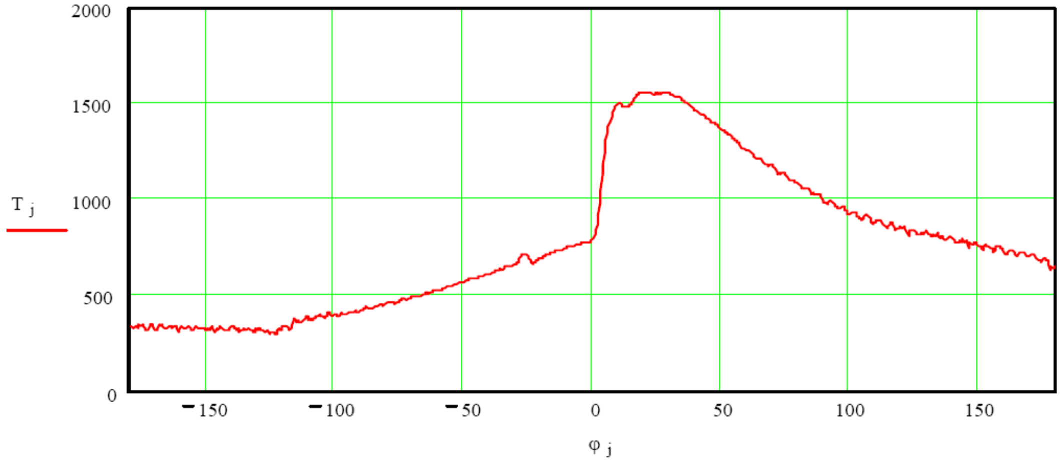
COMBUSTION PROGRESSIVITY



HEAT EMISSION



GAS TEMPERATURE IN CYLINDER



Diesel fuel combustion indicators

m - combustion pattern indicator:	m = 1.103
φm - crank angle at which the combustion rate is the maximum one:	φm = 3
xm - relative amount of emitted heat at the moment of φm;	xm = 0.225
(dx/dφ)max - the maximum fuel combustion rate:	Dmax = 0.1
φec - end of combustion crank angle:	φec = 56
φpg - combustion duration	φpg = 57.5
φ1/2 - duration of combustion of 1/2 of fuel.	φt05 = 7.5
(dQ/dτ)max the maximum actual heat emission rate (kcal/s)	MQτ = 0.022

Procedure of residual useful life assessment by the preset pattern of Fe ingress into lubrication oil and the actual burning oil consumption

Engine running time, h Rd: = 90 Oil running time, h Rm: -50 Average load, 0.2-1 Nsr: = 0.92

Forecasted running time Rp:= 60: Rated diesel service life, h R:=2000

Fe control matrices
running time, h concentration, ppm

t1: = 8

Oil burning consumption control matrices
running time, h topping up, g oil level, g sampling for analysis, g

T2: = 7

$$X1 := \begin{pmatrix} 0 \\ 7 \\ 14 \\ 21 \\ 28 \\ 35 \\ 42 \\ 50 \end{pmatrix} \quad Y := \begin{pmatrix} 0.3 \\ 82 \\ 96.6 \\ 120 \\ 157 \\ 117 \\ 116 \\ 122 \end{pmatrix}$$

$$X2 := \begin{pmatrix} 12.0 \\ 19.0 \\ 26.0 \\ 33.5 \\ 41.5 \\ 45.5 \\ 50.0 \end{pmatrix} \quad DM := \begin{pmatrix} 0 \\ 350 \\ 1200 \\ 1800 \\ 900 \\ 900 \\ 0 \end{pmatrix} \quad YM := \begin{pmatrix} 5062 \\ 4022 \\ 4211 \\ 4116 \\ 4589 \\ 4778 \\ 4967 \end{pmatrix} \quad OM := \begin{pmatrix} 100 \\ 100 \\ 100 \\ 100 \\ 100 \\ 0 \\ 100 \end{pmatrix}$$

Filtration coefficient Kf=Mf/Myg Kf: =0.1

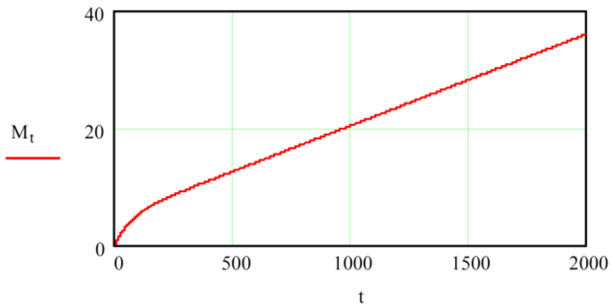
$t := 0..2000$ $\quad v(t) := 0.044 + 0.2 \cdot e^{-0.015 \cdot t}$ $\quad V_t := v(t)$

$$I := \left| \begin{array}{l} S \leftarrow 0 \\ \text{for } t \in 0..2000 \\ \quad \left| \begin{array}{l} S \leftarrow S + V_t \\ I_t \leftarrow S \end{array} \right. \\ I \end{array} \right.$$

$$M := \frac{I \cdot \left(0.545 - 2 \cdot Nsr + 3.467 \cdot Nsr^2\right)}{4.62}$$

$M_{2000} = 36.011$

Total Fe ingress into oil, g



Calculation of burning oil consumption, g/h

$$Gyg1 := \left| \begin{array}{l} \text{for } i \in 0..t2 - 2 \\ \quad Gyg1_i \leftarrow \dfrac{YM_i - YM_{i+1} + DM_i - OM_i}{X2_{i+1} - X2_i} \\ Gyg1 \end{array} \right.$$

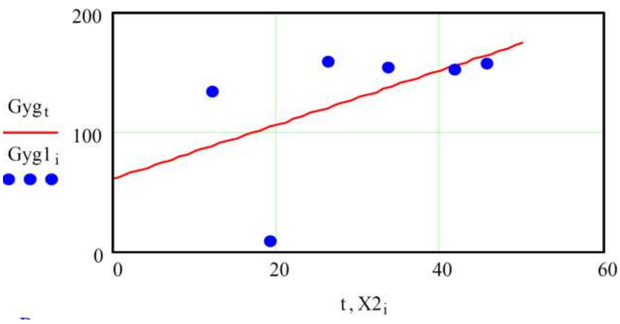
$\text{mean}(Gyg1) = 127.743$

Approximation of burning oil consumption, g/h

$i := 0..t2 - 2$ $\quad B_{i,0} := 1$ $\quad B_{i,1} := X2_i$

$$Gyg := \left| \begin{array}{l} C \leftarrow \left(B^T \cdot B\right)^{-1} \cdot B^T \cdot Gyg1 \\ \text{for } i \in 0..Rm \\ \quad Gyg_i \leftarrow C_0 + C_1 \cdot i \\ Gyg \end{array} \right.$$

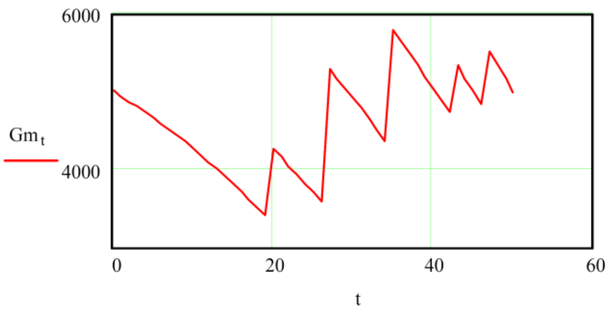
Burning oil consumption, g/h



Oil level calculation, g

```
Gm := | S ← 0
      | i ← 1
      | for  t ∈ 0.. Rm
      |   | S ← S + Gyg t
      |   | Gm t ← YM i−1 − S
      |   | if  t ≥ X2 i
      |   |   | S ← −DM i
      |   |   | i ← i + 1
      | Gm
```

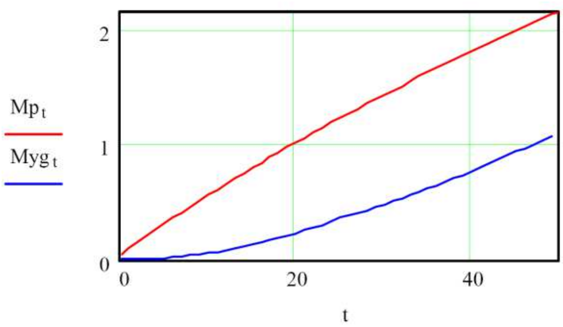
Oil level, g



Fe ingress calculation during the oil running period, g

```
Mp := | t ← 0
      | Sk ← 0
      | for  i ∈ Rd − Rm.. Rd
      |   | Sk ← Sk + (M i+1 − M i)
      |   | Mp t ← Sk
      |   | t ← t + 1
      | Mp
```

Total Fe ingress and burning, g



Calculation of total burning Fe consumption, g

```
Myg := | Sost ← 0
       | Sm ← 0
       | S ← 0
       | for  t ∈ 0.. X2 t2−1 − 1
       |   | Sost ← Sost + (Mp t+1 − Mp t − Sm)
       |   | Sm ← Sost · Gyg t+1 / Gm t+1
       |   | S ← S + Sm
       |   | Myg t ← S
       | Myg
```

$$Mp_{t1-1} = 0.416$$

$$Myg_{t1-1} = 0.029$$

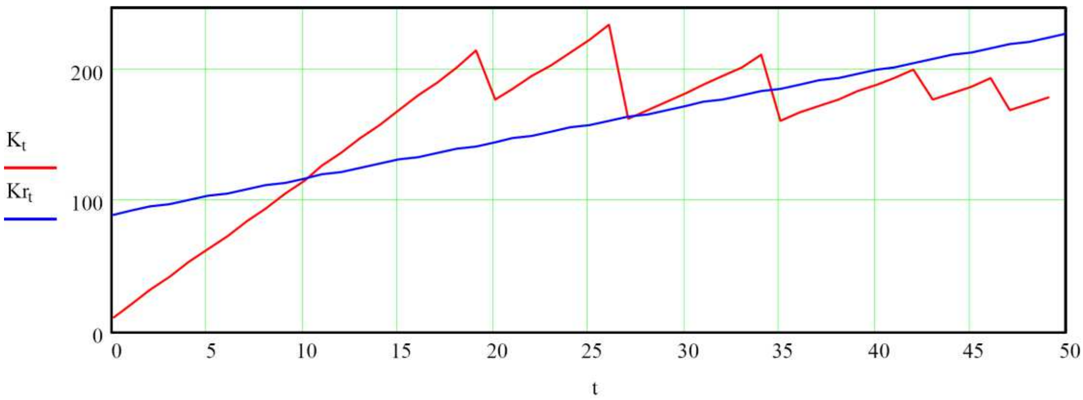
Calculation of Fe concentration in oil, g

```
K := | Sk ← 0
     | for  t ∈ 0.. Rm − 1
     |   | Sk ← Sk + (Mp t+1 − Mp t)
     |   | K t ← [Sk − (1 + Kf) · Myg t] / Gm t · 10^6
     | K
```

$i := 0..Rm - 1 \qquad B_{i,0} := 1 \qquad B_{i,1} := i \qquad C2 := \left(B^T \cdot B\right)^{-1} \cdot B^T \cdot K$

$$Kr := \left| \begin{array}{l} \text{for } i \in 0..Rp \\ \quad Kr_i \leftarrow C2_0 + C2_1 \cdot i \\ Kr \end{array} \right. \qquad C2 = \begin{pmatrix} 89.602 \\ 2.772 \end{pmatrix}$$

Dynamics of calculated Fe concentration in oil and its approximation, g/t



Linear model of actual concentration

$i := 0..t1 - 1 \qquad B1_{i,0} := 1 \qquad B1_{i,1} := X1_i \qquad n := t1$

$$T := \left| \begin{array}{l} ysr \leftarrow \text{mean}(Y) \\ C \leftarrow \left(B1^T \cdot B1\right)^{-1} \cdot B1^T \cdot Y \\ \text{for } i \in 0..n-1 \\ \quad yr_i \leftarrow \sum_{l=0}^{1} C_l \cdot B1_{i,l} \\ S \leftarrow \sqrt{\dfrac{\sum_{i=0}^{n-1} (yr_i - Y_i)^2}{n-3}} \\ R \leftarrow \dfrac{\sum_{i=0}^{n-1} (yr_i - ysr)^2}{\sum_{i=0}^{n-1} (Y_i - ysr)^2} \\ T \leftarrow \begin{pmatrix} S \\ R \\ C \end{pmatrix} \end{array} \right.$$

$$yr := \left| \begin{array}{l} C \leftarrow \left(B1^T \cdot B1\right)^{-1} \cdot B1^T \cdot Y \\ \text{for } i \in 0..n-1 \\ \quad yr_i \leftarrow \sum_{l=0}^{1} C_l \cdot B1_{i,l} \\ yr \end{array} \right.$$

$$yp := \left| \begin{array}{l} C \leftarrow \left(B1^T \cdot B1\right)^{-1} \cdot B1^T \cdot Y \\ yp_n \leftarrow C_0 + C_1 \cdot Rp \\ yp \end{array} \right.$$

Calculated and actual concentration values

$$yr = \begin{pmatrix} 55.322 \\ 68.41 \\ 81.497 \\ 94.585 \\ 107.673 \\ 120.76 \\ 133.848 \\ 148.805 \end{pmatrix} \qquad Y = \begin{pmatrix} 0.3 \\ 82 \\ 96.6 \\ 120 \\ 157 \\ 117 \\ 116 \\ 122 \end{pmatrix}$$

Residual model dispersion

$T_0 = 38.912$

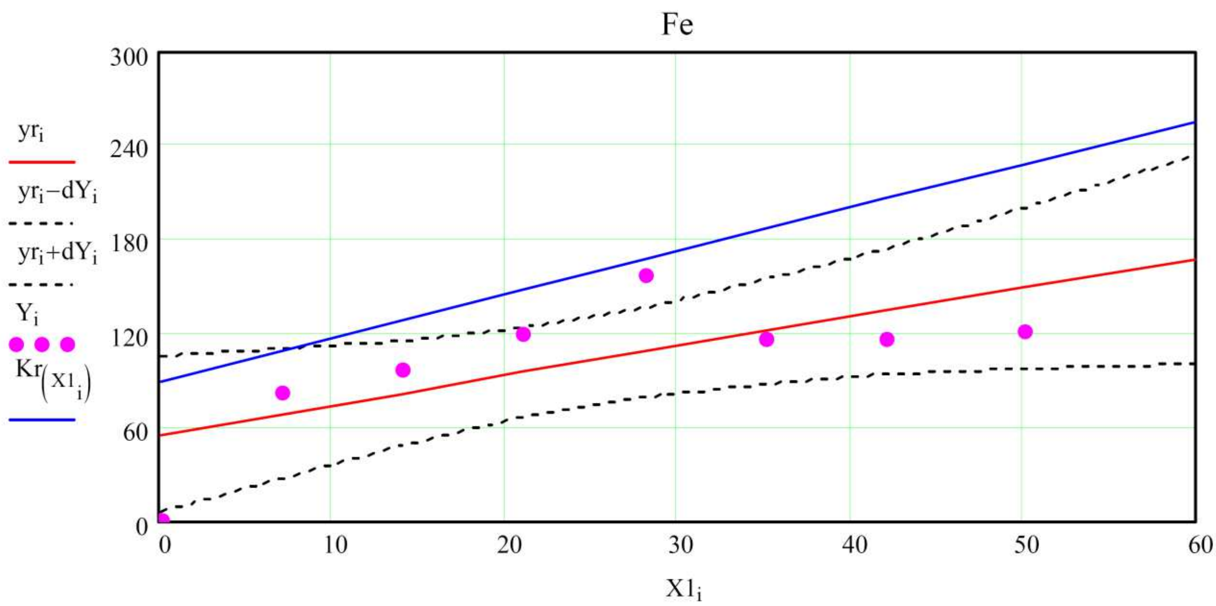
Multiple determination coefficient

$T_1 = 0.493$

$n := t1$ $\quad X1_n := Rp \quad yr_n := yp_n \quad i := 0..n \quad S := T_0$

$$dY := \left| \begin{array}{l} \text{for } i \in 0..n \\ \quad \left| \begin{array}{l} XL \leftarrow (1 \quad X1_i) \\ dY_i \leftarrow qt(0.95, n-3) \cdot S \cdot \left| \sqrt{XL \cdot \left((B1)^T \cdot B1\right)^{-1} \cdot (XL)^T} \right| \end{array} \right. \\ dY \end{array} \right.$$

$C := T_2$



Actual Fe concentration change rate (g/t/h) $\quad C1 = 1.87$

Calculated Fe concentration change rate (g/t/h) $\quad C21 = 2.772$