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NEDERLANDS SCHEEPS-STUDIECENTRUM TNO

NETHERLANDS SHIP RESEARCH CENTRE TNO

ENGINEERING DEPARTMENT LEEGHWATERSTRAAT 5, DELFT

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RESIDUAL FUEL TREATMENT ON BOARD SHIP

PART II

COMPARATIVE CYLINDER WEAR MEASUREMENTS ON A LABORATORY DIESEL ENGINE USING FILTERED OR CENTRIFUGED RESIDUAL FUEL

(VERGELIJKENDE CILINDERSLIJTAGEMETINGEN AAN EEN LABORATORIUM DIESELMOTOR BIJ TOEPASSING VAN GEFILTREERDE OF GECENTRIFUGEERDE RESIDUALE BRANDSTOF)

by

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VOORWOORD

Het streven naar vereenvoudiging van de, in de machinekamer van het zeegaande schip voorkomende, werktuigen en systemen heeft o.a. geleid tot oriënterend experimenteel onderzoek naar de mogelijkheden de gebruikelijke behandelingsmethode van de residuale brandstof van de hoofdmotor te vervangen door filtreren.

De talrijke in de literatuur verschenen publikaties demonstreren de in rederskringen bestaande belangstelling voor dit onderwerp.

Alvorens tot experimenten aan boord over te gaan, werd het door de Nederlandse reders nuttig geoordeeld aan een, met een scheepshoofdmotor in zekere mate vergelijkbare, laboratoriummotor oriënterend onderzoek te verrichten.

De bij dit onderzoek gevolgde werkwijze, de resultaten en de interpretatie hiervan en de conclusies worden in dit rapport beschreven.

De resultaten wettigen de verwachting dat de toepassing van een goed werkend brandstoffilter in plaats van de gebruikelijke centrifuges, het economisch verantwoord functioneren van de hoofdmotor niet zal belemmeren.

Langdurige experimenten onder strenge controle aan boord van een aantal schepen met motoren van verschillend type en fabrikaat en met brandstoffen van verschillende herkomst zijn noodzakelijk om een gefundeerde conclusie te kunnen trekken.

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PREFACE

Efforts to simplify the equipment of the engine room of a seagoing ship have inter alia inspired preliminary experimental investigations aiming at the replacing of the conventional treatment of the main engine's residual fuel by filtration.

Shipowners are greatly interested in this subject, as is evident from several publications.

The Dutch shipowners decided to have preliminary research carried out on a laboratory engine which would be comparable with a ship's main engine, before proceeding to shipboard experiments.

The present report gives the method followed in this research project, its results, the interpretation thereof, and the conclusions. The results look promising in that application of a properly operating fuel filter, instead of the usual centrifuges, will be no impediment to the economically justified performance of the main engine.

To enable a well-founded conclusion, adequately controlled long term experiments will have to be carried out on board ship, using engines of different types and makes as well as fuels from different sources.

THE NETHERLANDS SHIP RESEARCH CENTRE TNO

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Summary

This report presents the results of comparative experimental investigations on the influence of fuel treatment on the wear of cylinder liners and piston rings of a two cylinder two-stroke cycle laboratory diesel engine, using filtered or centrifuged residual fuel.
The results indicate that the wear rate of the engine, under the operational conditions of the experiments, did not differ significantly for filtered fuel, using a 10 μ filter, from that when using centrifuged fuel under the same conditions.

1 Introduction

For economic reasons, shipowners try to reduce the complements of their ships. This trend has resulted in the development of systems, tools and equipment aiming at reducing the operation repair- and maintenance activities in the engine room. The investigations described in the present report link up with these developments, because in the author's opinion, a properly designed residual fuel filter system is more reliable, and requires less operation and investment costs than the usual centrifuge system.

Cylinder liner wear has been considerably reduced by the application of alkaline cylinder lubricants and the improved liner materials [3]. This has raised the question whether centrifuging of the fuel is imperative for economic operation of the main engine or that it may be replaced by a simple filtration process.

To investigate the wear rate of the cylinder liner and piston rings, tests were carried out on a laboratory engine. The design of the engine is comparable with that of a two-stroke cycle single-acting marine engine. The residual fuel used was either centrifuged or filtered.

2 Experimental work

The tests were carried out on a two cylinder, single-acting, two-stroke cycle, normal aspirated, crosshead engine in the builder's laboratory.

2.1. *Data*

2.1.1. Engine (fig. 1)

Builder:	Machinefabriek Bolnes N.V., Krimpen aan de Lek (Holland)
Number of cylinders:	2
Cycle:	two-stroke
Bore:	190 mm
Stroke:	350 mm
Speed:	428 r.p.m.
Output:	100 SHP
Scavenging:	uniflow system

2.1.2. Fuel used

The analysis of the fuel is given in table 1.

TABLE 1. Specification of the fuel used

Test	Dimension	
Specific gravity at 60 °F	g/cm³	0.9640
Calorific value	Kcal/Kg	10,220
Viscosity at 100 °F	secs Redwood No. 1	3,065
Flash point	°C	120
Pour point	°C	16
Conradson carbon	wt%	9.5
Ash	wt%	0.03
Water	vol %	0.1
Asphalt	wt %	3.7
Sulphur	wt %	3.06
Vanadium	ppm	107
Sodium	ppm	53

2.1.3. Crankcase lubricating oil used

The crankcase lub oil used was B.P. Energol OE 15, which is a straight mineral oil.

Table 2 gives the specifications at the beginning and at the end of the tests.

2.1.4. Cylinder lubricating oil used

The cylinder liners were lubricated with B.P. Energol CLO 40 M, a cylinder oil as specified in Table 3.

TABLE 2. Specifications of crankcase lub oil before and after the tests

Test	Dimension	Before the tests	After the tests
Specific gravity	gr/cm³	0.900	0.9029
Viscosity at 100 °F	cS	127.8	—
„ „ 122 °F	cS	67.0	72.9
„ „ 140 °F	cS	42.5	46.5
„ „ 210 °F	cS	11.76	—
Total acid number	mg KOH/g	—	0.45
Insoluble in n-heptane	wt %	—	0.49
Insoluble in n-benzene	wt %	—	0.21

TABLE 3. Specification of the cylinder lub oil

Test	Dimension	
Specific gravity at 60 °F	g/cm³	0.956
Flash point	°C	230
Pour point	°C	–9
Viscosity at 100 °F	cS	185.2
„ „ 122 °F	cS	96.0
Total base number	mg KOH/g	54

2.1.5. Fuel purification system

Fig. 2 shows the arrangement of the purification system. For purification of the fuel, a purifier Titan, type CMA-1310 and a 10 micron mesh self-cleaning filter, Kwant, type F 008237 were installed.

Two storage tanks were used for the centrifuged and filtered fuel. The existing pipe system was adapted to the requirements of the comparative tests.

2.1.6. Operating conditions

During the tests, the engine was driving an alternator supplying constant power.

The load was 95% of the nominal engine load. The temperatures of the exhaust gases were: 322 °C for cylinder 1, and 334 °C for cylinder 2.

Before the engine, the temperature of the cooling water was 61 °C, and after the engine 71 °C.

The scavenging air temperature was 71 °C, and the scavening air pressure was 0.186 kgf/cm². Maximum pressures amounted to 68 kgf/cm² for cylinder 1 and 70 kgf/cm² for cylinder 2.

Near the engine, the fuel temperature was 126 °C; the associated fuel viscosity was 80 secs Redwood No. 1.

The engine was fitted with cast iron liners and the upper piston rings were chromium plated.

The liners had been in service during 1000 hours, the piston rings during 250 hours.

When the fuel was treated with the filter, this had to be cleaned when the pressure difference

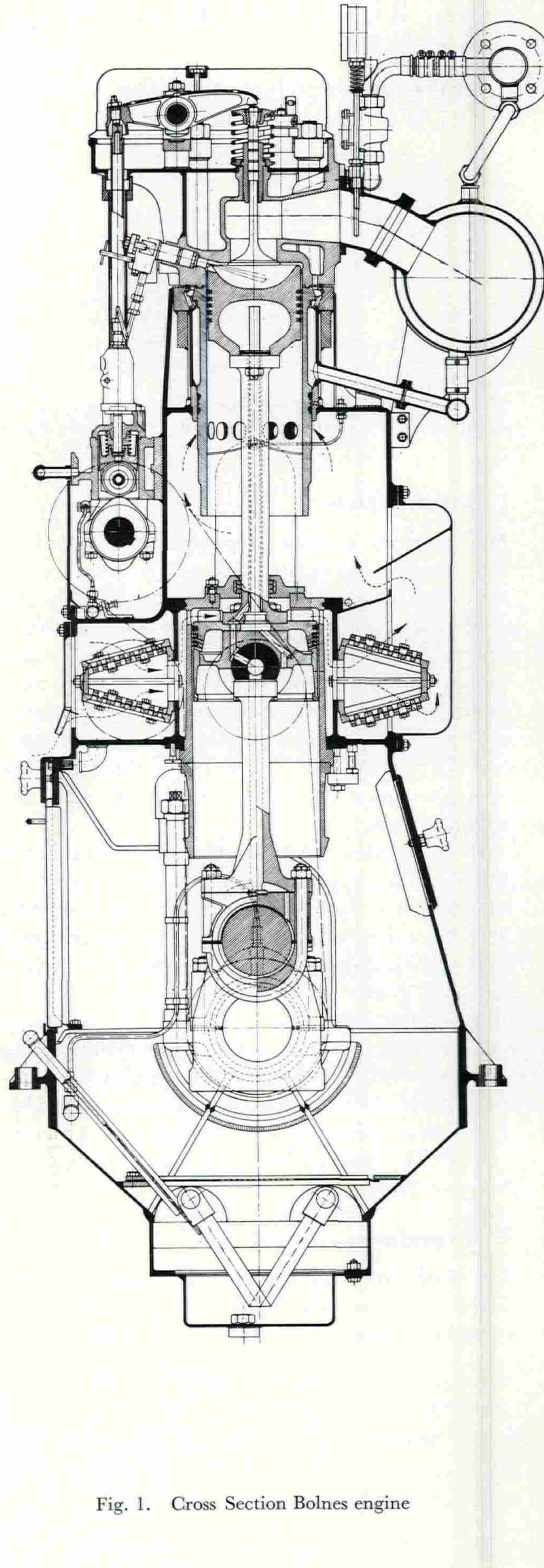

Fig. 1. Cross Section Bolnes engine

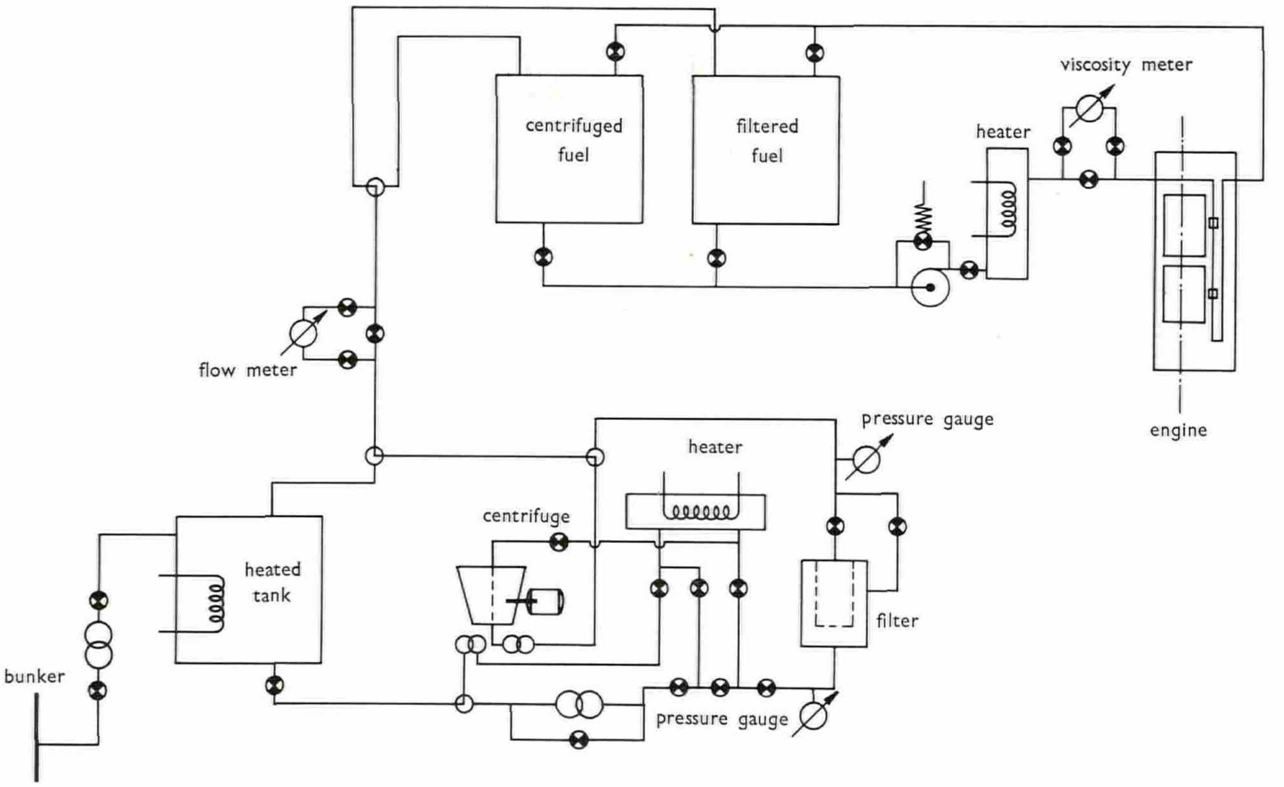

Fig. 2. Arrangement of purification system

across the filter amounted to 0.5 kgf/cm². This figure was reached at a throughput of 40 liters fuel. The consumption of cylinder lubricating oil had been adjusted to 0.85 g/SHPh. For normal operation, 0.7 g/SHPh is sufficient. The higher consumption during the tests was necessary in view of the accuracy of the measuring method applied.

2.2. *Wear measurements*

2.2.1. Method used

For comparison of the wear rate, occurring when centrifuged or filtered fuel was used, the quantity of iron carried off with the cylinder lubricating oil, during sandwich operation periods of 48 hours with each of these fuels, was measured.

This quantity of iron was determined by measuring the iron content of the cylinder oil scraped off by the piston rings and assuming that this equals the iron content of the cylinder oil lost through the combustion chamber [6], [7], [8], [11].

In order to collect the drip-oil, emerging from the mouth of the cylinder liners, simple circular gutters were built round the exposed outer ends of the liners (fig. 3).

The iron content was determined by a photometric method, using α, α' dipyridil as a reagent.

By accurately measuring the quantity of cylinder lubricating oil supplied to each cylinder, the drip-oil percentage of it could be determined.

It was assumed that the contamination of the drip-oil by crankcase lubricant through the piston rod gland, is not affected by the fuel treatment and, accordingly, does not effect the measurement of the wear rate difference.

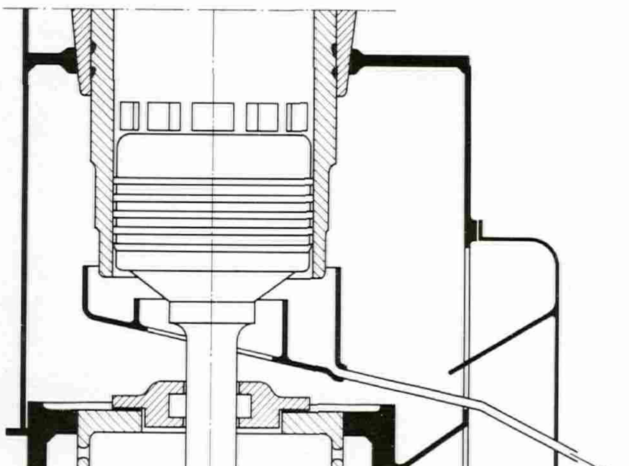

Fig. 3. Cylinder drip-oil collecting device

In order to get an impression of the wear within a period of 48 hours, the collection period was taken at 6 hours, so that in each test period 8 samples of cylinder drip-oil were obtained from each cylinder.

For this purpose, the test rig had been provided with an automatically operating mechanism which ensured the drip-oil flowing from the gutters to be collected in a different bottle with intervals of 6 hours. In this way, automatic sampling during 24 hours was realised.

Fig. 4 is a photograph of this arrangement showing the pulse timer and the solenoid valves. The tests were run for 96 hours without interruption. Each period of interruption was used to replace the fuel nozzles and to correct, if necessary, the cylinder lub oil pumps.

The total running time of the tests was 384 hours, subdivided into 4 periods during which filtered fuel and 4 periods during which centrifuged fuel was used.

The test programme was:
filtered fuel – centrifuged fuel – stop (48 hours)
filtered fuel – centrifuged fuel – stop (72 hours)
centrifuged fuel – filtered fuel – stop (72 hours)
centrifuged fuel – filtered fuel.

The piston rings were weighed accurately before and after the tests. The diameters of the cylinder liners were measured at seven positions of the cylinder centre line, by comparison with a calibrated ring, thus eliminating the temperature influence, also before and after the tests.

The average of the diameters at four positions of the liner circumference was considered to be the diameter at the corresponding position of the centre line.

Measuring of cylinder liners during the tests was considered undesirable in view of the wear rate being possibly influenced by dismantling.

The quantity of material lost by wear was calculated with the data thus obtained.

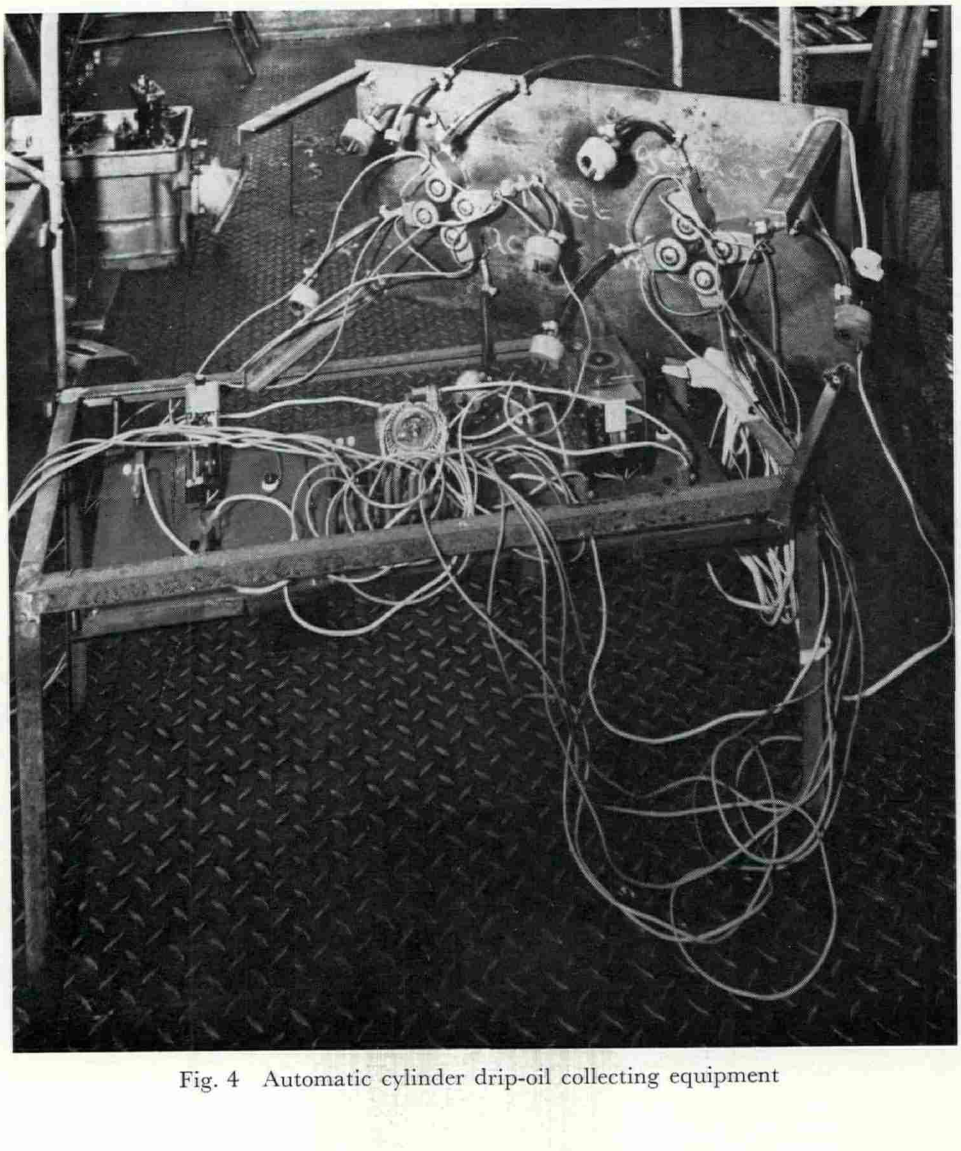

Fig. 4 Automatic cylinder drip-oil collecting equipment

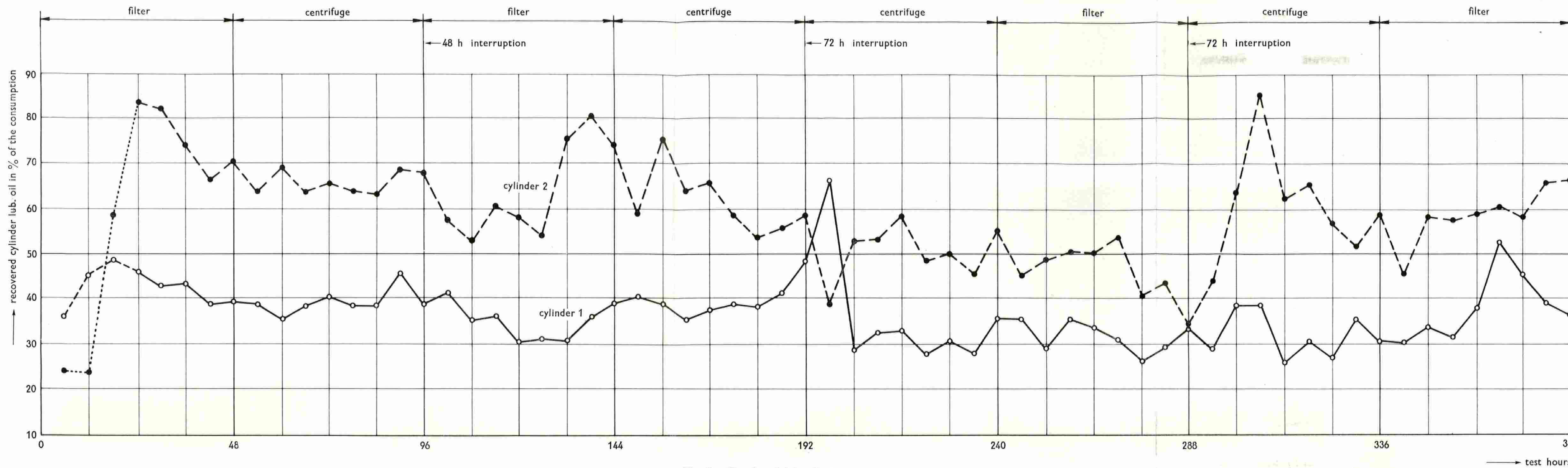

Fig. 5. Results of drip-oil measurements

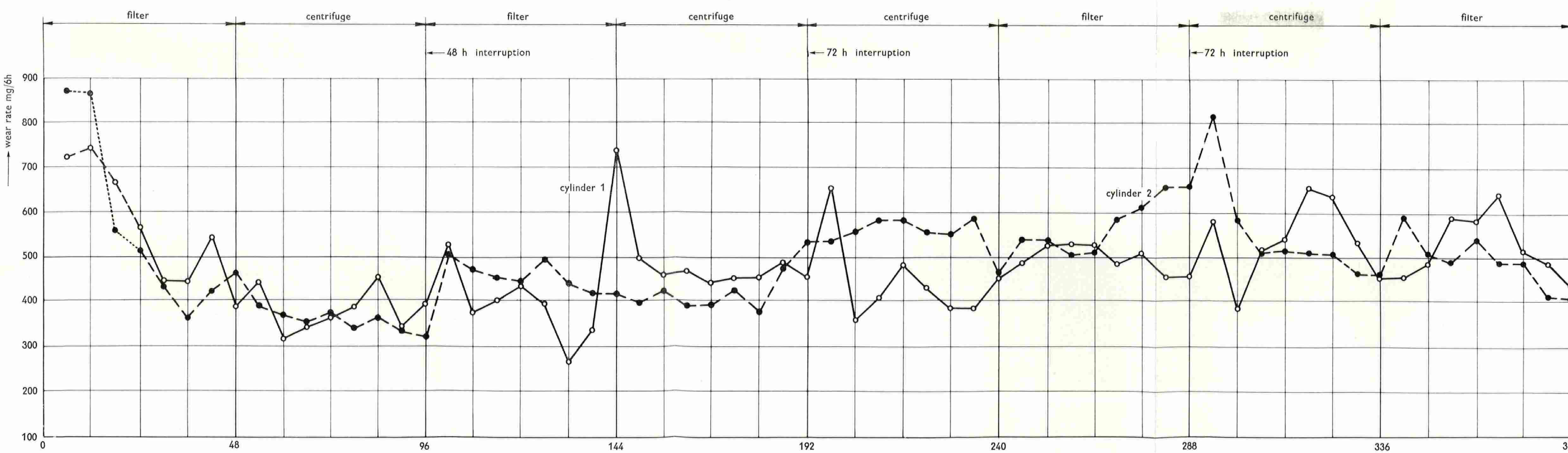

Fig. 6. Results of wear rate measurements

2.2.2. Results

From the data obtained as described in par 2.2.1. the wear rate of each cylinder, expressed in mg iron per 6 hours, was calculated. The results of this calculation are plotted in fig. 6 against test hours.

Fig. 5 presents the recovered drip oil expressed in percentage of the cylinder lub oil consumption also plotted against test hours.

Table 4 gives the measured and calculated weight losses of piston rings and cylinder liners.

TABLE 4. Measured and calculated weight loss of piston rings and liners

Item	Weight loss g	
	Cylinder 1	Cylinder 2
Liner	75	33.5
Piston ring 1 (top)	7.867	3.257
,, ,, 2	3.864	3.699
,, ,, 3	2.975	4.012
,, ,, 4	2.861	2.193
,, ,, 5	4.156	3.497
Total	96.723	50.158

3 Analyses of the results

The results presented in figures 5 and 6 were analysed statistically. Whereas the first three measurements are considered unreliable, they are not taken into account. Because the results were found to be dependent on the period and number of observations, and because the number of measurements per period was low, they are not presented in histograms. Two analyses of variance with three criteria were carried out. These criteria are:

a Fuel treatment (centrifuged or filtered)
b Period in which the results were obtained
c Cylinder to which the result relates (cylinder 1 or cylinder 2).

For each combination of cylinder and fuel treatment, there are four periods.

The confidence intervals of the wear rates and of the difference in wear rate when either filtered or centrifuged fuel was used, were determined by Scheffé's method.

3.1. *Results of statistical analysis*

From the analysis of the results the following was concluded.

1. There is no significant difference in wear rate between the methods of fuel treatment applied. The calculated confidence intervals of the wear rates of centrifuged and filtered fuel are presented

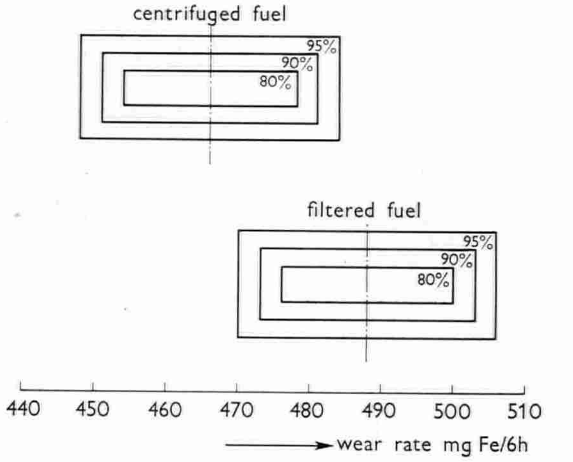

Fig. 7. Confidence intervals of the measured wear rates

in fig. 7. The calculated confidence intervals, of the difference in wear rate for filtered and centrifuged fuel are given in Table 5, and presented in fig. 8.

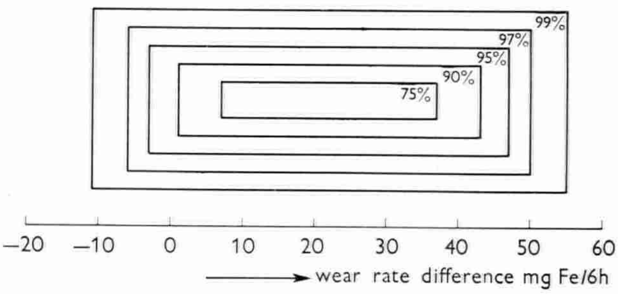

Fig. 8. Confidence intervals of the difference in wear rate for filtered – and centrifuged fuel

TABLE 5. Confidence intervals of the difference in wear rate for filtered and centrifuged fuels

Confidence level	Lower limit mg iron per 6 hrs	Upper limit mg iron per 6 hrs
0.75	7	37
0.90	1	43
0.95	– 3	47
0.975	– 6	50
0.99	–11	55

From the data of Table 5, and with the aid of the mean wear rate for centrifuged fuel, it was derived that, at a confidence level of 95%, the wear rate of filtered fuel is less than 10% higher than the wear rate of centrifuged fuel.

2. There are significant differences in the percentages of cylinder drip oil and in the wear rates between the periods. The confidence level of this conclusion is 99.9%.

3. There is a significant difference between the cylinders regarding the percentages of cylinder drip oil. Cylinder 2 has, on average, a higher percentage of drip oil than cylinder 1.
   The confidence level of this conclusion is also 99.9%. The drip oil quantity recovered from cylinder 2 is 20% higher than that of cylinder 1 The confidence level of this conclusion is 95%.

4. There is no significant difference between the cylinders regarding the wear rate.

5. There is no agreement between the total wear determined by the drip oil analysis method and that determined from the weight loss of the piston rings and the diameter increase of the cylinder liners.

4 Interpretation of results

1. The results reported in (1) of par. 3.1. imply that the differences in wear rate between the methods of fuel treatment, as established in the investigations, might be due to factors affecting the wear rate other than the fuel treatment.

2. The result reported in (2) implies that the levels of the measured variables differ in the periods of testing. Consequently, an explanation for this aspect must be sought in factors, varying in time, which also influence the variables measured. Such factors may be for example
   a. the quality of the combustion process, which depends on several conditions, and which may affect the wear rate;
   b. the crankcase lubricating oil carried along by the piston rod, which contaminates the cylinder drip oil and thus affects the quantity as well as the iron content of the drip oil.

3. The difference between the two cylinders regarding the percentages of drip oil as reported in (3), may originate from the difference in performance of the scraper rings. The disagreement between the total wear figures determined by different methods may be due to several possible causes. For example:
   a. the inaccuracy of the cylinder diameter measurement;
   b. the small changes in cylinder diameter due to thermal stresses which occurred in the period of testing;
   c. the influence of the drip oil contamination by crankcase lubricant.

4. In points (3) and (4) of par. 3.1. (Results of statistical analysis) it is concluded that cylinder 1 is not different from cylinder 2 as regards the wear rate, but that the former cylinder does differ from the latter with regard to percentage of drip-oil.
   This result adds to our confidence in the applied method of wear measurement.

5 Conclusions

1. The applied cylinder oil analysis is a simple method to obtain an indication of the wear rate of an engine cylinder by shortterm tests.
   This method can be refined by increasing the number of measurements and by determining the contamination of the cylinder-oil sample by crankcase lubricant, e.g. by adding an easily detectable tracer to this oil.

2. The wear rates of the cylinders of the engine and the operation conditions under consideration show no significant differences between centrifuged and filtered fuel.

3. Although the construction of the engine used shows similarities with a ship's main engine and the fuel and lubricants used were identical, it is not justifiable to extrapolate numerically the obtained results in view of the diverging construction and operational conditions of a marine engine.

4. However, the results of the tests suggest that application of a properly operating 10 micron fuel filter instead of centrifuges, will not substantially affect the cylinder liner wear.

6 Future work

In order to obtain a reliable picture of the difference in cylinder wear of marine engines when either filtered or centrifuged fuel is used, it is desirable to carry out comparative wear measurements aboard a number of ships equipped with main engines of several types and makes, under normal operational conditions, using filtered and centrifuged fuels.

To protect the fuel injection equipment, precautions will then have to be taken for efficient control of the water content and, if necessary, water separation of the fuel.

The reliability of results requires these tests to be carried out in such a way that all factors affecting wear are strictly controlled.

In view of the results, and the experience, obtained so far through the investigations reported, it is to be expected that the method applied is suitable for application in a full-scale research on board ship.

As a preliminary to this research, it is recommendable to carry out laboratory investigations on the wear of fuel injection equipment when filtered fuel is used, and also to investigate what simple effective means are available to keep the water content of the fuel below a permissible maximum. For these purposes, use of a heated settling-tank, atomization of the heated fuel above the daily service tank level or one single centrifuge, should be considered.

7 Acknowledgement

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The analyses of the oil samples were done by the Chemical Laboratory of the Central Technical Institute TNO.

The tests results were analysed by the Statistics Department TNO, and the automatic sampling equipment was designed by the Low Cost Automation section of the Industrial Liaison Department TNO.

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M = engineering department S = shipbuilding department C = corrosion and antifouling department

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NEDERLANDS SCHEEPSSTUDIECENTRUM TNO

NETHERLANDS SHIP RESEARCH CENTRE TNO
ENGINEERING DEPARTMENT LEEGHWATERSTRAAT 5, DELFT

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RESIDUAL FUEL TREATMENT ON BOARD SHIP

PART III

COMPARATIVE SHIPBOARD MEASUREMENTS OF CYLINDER LINER AND PISTON RING WEAR ON MAIN ENGINES USING FILTERED OR CENTRIFUGED RESIDUAL FUEL

DEEL III
(VERGELIJKENDE CILINDER- EN ZUIGERVEERSLIJTAGEMETINGEN AAN HOOFDMOTOREN BIJ TOEPASSING VAN GEFILTREERDE OF GECENTRIFUGEERDE RESIDUALE BRANDSTOF)

by

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RESEARCH COMMITTEE

VOORWOORD

Als vervolg op het oriënterend laboratoriumonderzoek naar de invloed van de brandstofbehandeling op onoplosbare bestanddelen en de cilinderslijtage [11], [12], werd een vergelijkend praktijkonderzoek uitgevoerd gedurende een aantal reizen op een tweetal schepen te weten het m.s. „Algorab" en het m.s. „Congokust". De hierbij toegepaste behandelingsmethoden waren centrifugeren en filtreren.

De bij dit praktijkonderzoek gevolgde werkwijze, de bewerking van de meetresultaten, de interpretatie van de uitkomsten en de conclusies worden in dit rapport beschreven.

Geconcludeerd wordt dat geen verschil in cilinder en zuigerveerslijtage, als gevolg van de brandstofbehandelingsmethoden, optreedt.

De resultaten van dit en eerder verricht onderzoek wettigen de verwachting dat filtratie van de brandstof het economisch verantwoord functioneren van de hoofdmotor niet zal belemmeren.

Een aanzienlijke vermindering van de investerings- en onderhoudskosten kan echter door toepassing van bedrijfszekere zelfreinigende filters worden bereikt.

Ervaring op langere termijn zal nodig zijn ter beoordeling van het slijtagegedrag van brandstofinspuitorganen bij gebruik van gefiltreerde brandstof.

Tevens zal aandacht moeten worden besteed aan een doelmatige controle en beheersing van het watergehalte van de brandstof.

NEDERLANDS SCHEEPSSTUDIECENTRUM TNO

PREFACE

Extending the preliminary laboratory investigations into the effect of fuel treatment on the unsolubles and cylinder wear [11], [12], comparative shipboard measurements were carried out on the main engines of two ships viz. m.s. „Algorab" and m.s. „Congokust" under normal service conditions.

The present report describes the method used, the results, the interpretation of the statistical analysis of the wear data obtained and the conclusions.

The conclusion is that no difference of cylinder liner- and piston ring wear occurred due to the two methods of fuel treatment used.

The results of the tests under consideration and of the experimental work carried out earlier indicate that proper fuel filtration will not affect the performance of the engine.

A considerable gain however, in first- and maintenance costs can be obtained by the application of a reliable selfcleaning filter. Long term experience will be necessary to show the effect of the fuel treatment on the wear of injection equipment.

Attention has also to be paid to a reliable and proper control of the water content.

NETHERLANDS SHIP RESEARCH CENTRE TNO

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RESIDUAL FUEL TREATMENT ON BOARD SHIP

PART III

COMPARATIVE SHIPBOARD MEASUREMENTS OF CYLINDER LINER AND PISTON RING WEAR ON MAIN ENGINES USING FILTERED OR CENTRIFUGED RESIDUAL FUEL

by

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Drs. G. G. VAN DER MEULEN

Summary

To investigate the effect of two residual fuel purification methods comparative cylinder liner and piston ring wear measurements were carried out on the main engines of two different ships, under normal operating conditions during several voyages.
The results indicate that the wear rate of the engines did not differ significantly for the fuel treatments used.

1 Introduction

Modern development in marine engineering tends among others to the application of highly reliable equipment and systems. For statistical reasons it can be stated that reliability increases without increasing maintenance if a function is performed by simpler means.

A critical survey of the reason for and the method of purification of residual fuel on board ship throughout the history of its application on diesel engines leads to the conclusion that in the early days centrifuging was the only effective method to reduce the water and impurities content which were considered to be responsible for the heavy cylinder liner wear experienced.

The remarkable reduction of cylinder liner and piston ring wear caused by the introduction of high alkaline lubricants and improved materials have raised the question whether the complicated fuel oil treatment is imperative for reliable and economic operation of the engine.

The raise of this question stimulated the investigation into the effectiveness and consequences of fuel treatment by filtering.

In the first report on the subject [12] the effect of centrifuging, filtering and homogenizing on the unsolubles in residual fuels of several sources was investigated.

The second report [13] dealt with cylinder liner and piston ring wear tests on a medium speed laboratory engine using filtered or centrifuged fuel. The encouraging results obtained from this work have lead to similar shipboard experiments described in this report.

The tests were carried out on the main engines of the m.s. ,,Algorab" and the m.s. ,,Congokust" during three respectively two voyages under normal service conditions.

2 Experimental work

The measurements were carried out on the main engines of the m.s. ,,Algorab and the m.s. ,,Congokust".

2.1 *Data*

2.1.1 Main Engines

	m.s. ,,Algorab"	m.s. ,,Congokust"
Builder	Stork N.V., Hengelo (Holland)	Werkspoor N.V., Amsterdam (Holland)
Type	Hotlo 750/1600	KMWS 720/1400
Number of cylinders	6	6
Cycle	two-stroke	four-stroke
Bore	750 mm	720 mm
Stroke	1600 mm	1400 mm
Speed	115 r.p.m.	115 r.p.m.
Output	7200 SHP	3000 SHP
Scavenging	uniflow	–
Turbocharging	pulse system	–

2.1.2 Crankcase lubricating oil used

The crankcase lubricating oil used for both engines was Mobil DTE 3.

2.1.3 Cylinder lubricating oil used

The cylinder liners of both engines were lubricated with Mobilgard 493, as specified in Table 1.

2.1.4 Fuel used

The fuel used aboard the m.s. ,,Algorab" was a resi-

Table 1. Specification of the cylinder lubricating oil used

Test	Dimension	
Specific gravity at 15 °C	g/cm³	0.927
Flash point	°C	207
Pour point	°C	15
Viscosity at 20 °C	cS	760
50 °C	cS	100
100 °C	cS	14.4
Total Base Number	mg KOH/g	40

dual fuel with a viscosity of about 3500 secs. Redwood I at 100 °F. The bunker port was Las Palmas.

The m.s. „Congokust" used a fuel, the viscosity of which being in the range of 1200–1500 secs. Redwood I at 100 °F.

Specifications of the fuels used during the tests are given in the Tables 2, 3, 4, 5 and 6.

The figures mentioned are the results of the analysis of fuel samples taken at regular intervals during the test periods.

2.1.5 Fuel purification systems

a. m.s. „Algorab"

The fuel purification system consisted of a storage tank, from which the fuel was directed through a purifier, make Westfalia type SAOG 4016, a buffer-tank and a clarifier, make Westfalia type MOC 8015, to the clean heavy oil tank.

From this tank the fuel was fed to the engine after passing a 40 micron mesh Winslow filter, type KW-28-F.1240.C, and a 46 micron air mesh filter.

The existing pipe system was modified in such a way that the engine could consume the fuel directly from the storage tank as well as from the clean heavy oil tank in both cases after passing the Winslow filter and the air-mesh filter.

The Winslow filter by-pass, installed in order to prevent engine stoppage in case the filter clogged, has never been used.

b. m.s. „Congokust"

The fuel purification system of the m.s. „Congokust" was quite similar to that of the m.s. „Algorab". The clarifier, however, was manufactured by Laval, type VIB 1929 C, and the purifier was an automatically discharging Titan unit of the M.S. 66 type. The filter used was a 0.003″ mesh self-cleaning AutoClean filter in the main engine fuel circulating system.

2.1.6 Operating conditions

In order to avoid the influence of engine load on the liner and piston ring wear the measurements were carried out only under steady state full load conditions of the engines during the longest part of a normal voyage.

During the test periods, engine load was checked every twelve running hours by recording the scavenge air and exhaust gas temperature, speed and fuel consumption. Moreover indicator diagrams were taken of each cylinder every twentyfour running hours.

The cylinder liners were lubricated with the same amount of oil effectuated after careful adjustment of the lubricators. The lub. oil consumption during twelve running hours was measured.

Some nautical data viz. windforce, winddirection and condition of the sea were also measured at regular time intervals. No pistons were drawn during the voyages under consideration. The data obtained are summarized in Figures 1, 2 and 3.

2.2 *Wear measurements*

2.2.1 Method used

a. *m.s. „Algorab"*

For comparison of the wear rate of cylinder liners and piston rings occurring when centrifuged or filtered residual fuel is used the iron content of the cylinder drain oil emerging from the diaphragm separating the upper part of the crankcase from the cylinder is used [7], [13].

During the test periods of the two voyages the fuel was purified in accordance with the following scheme.

First voyage:

from January 21st to February 1st 1967:	filter
from February 28th to March 11th 1967:	centrifuge + filter

Second voyage:

from March 29th to April 10th 1967:	filter
from May 6th to May 18th 1967:	centrifuge + filter

At the end of every twelve running hours, during the measuring periods, a sample of drain oil was taken. In this way some 22 oil samples of every cylinder were obtained in every period.

Because the engines under investigation could not be provided with a gutter round the exposed outer end of the cylinder liner contamination of cylinder drip oil by crank case oil had to be accepted.

During the test periods of the third voyage, from November 23rd 1967 to January 30th 1968, sandwich measurements were carried out because it was noticed that the engine load had been higher during the fourth period as compared with the preceding periods.

Every 48 hours the fuel treatment was changed. During these tests the total amount of oil emerging from the diaphragm separating the upper part of the crankcase from the cylinder of each cylinder was collected during twelve running hours.

This quantity was measured and a sample was taken after careful homogenizing by stirring.

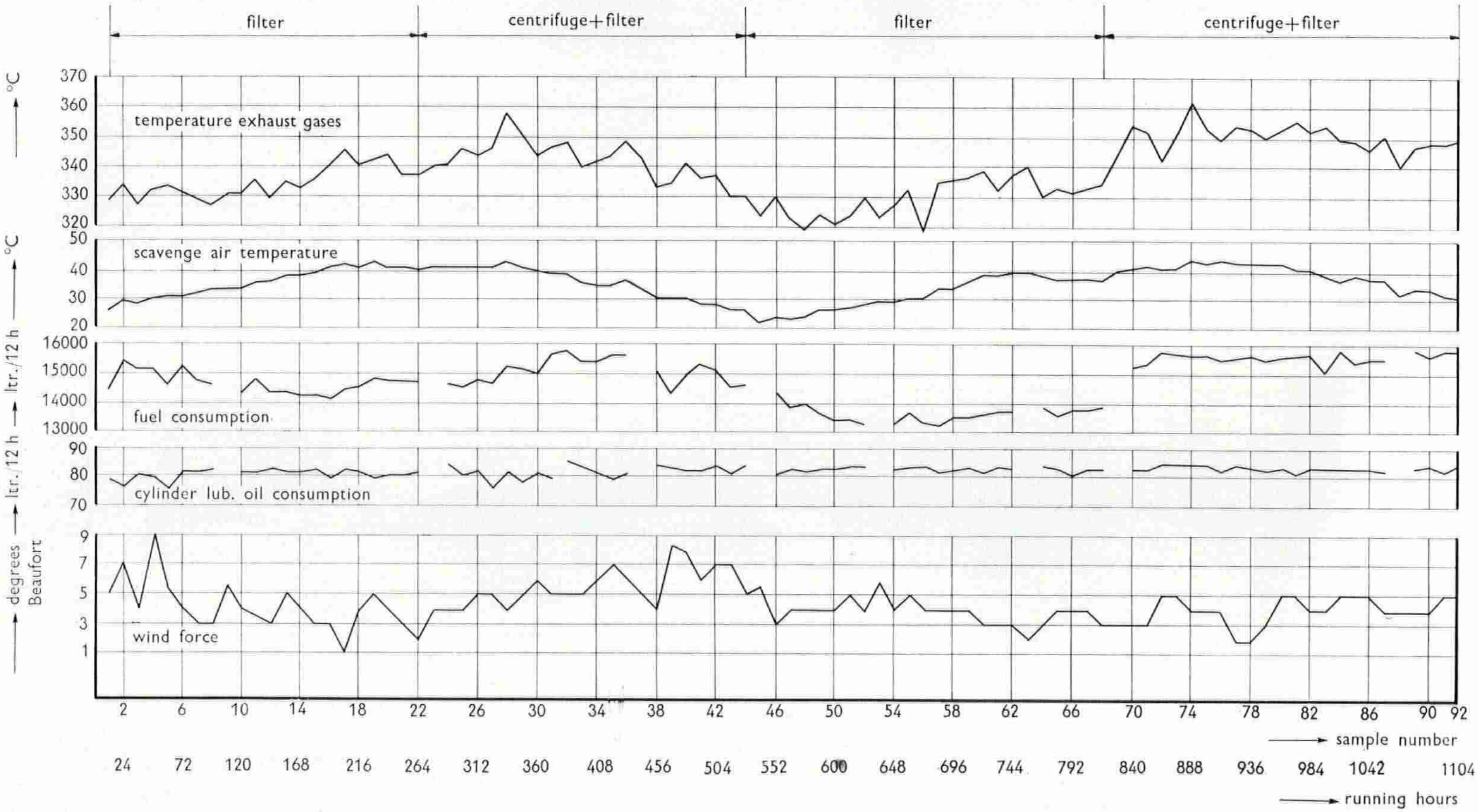

Fig. 1. Some service conditions during the first two voyages of the m.s. „Algorab”

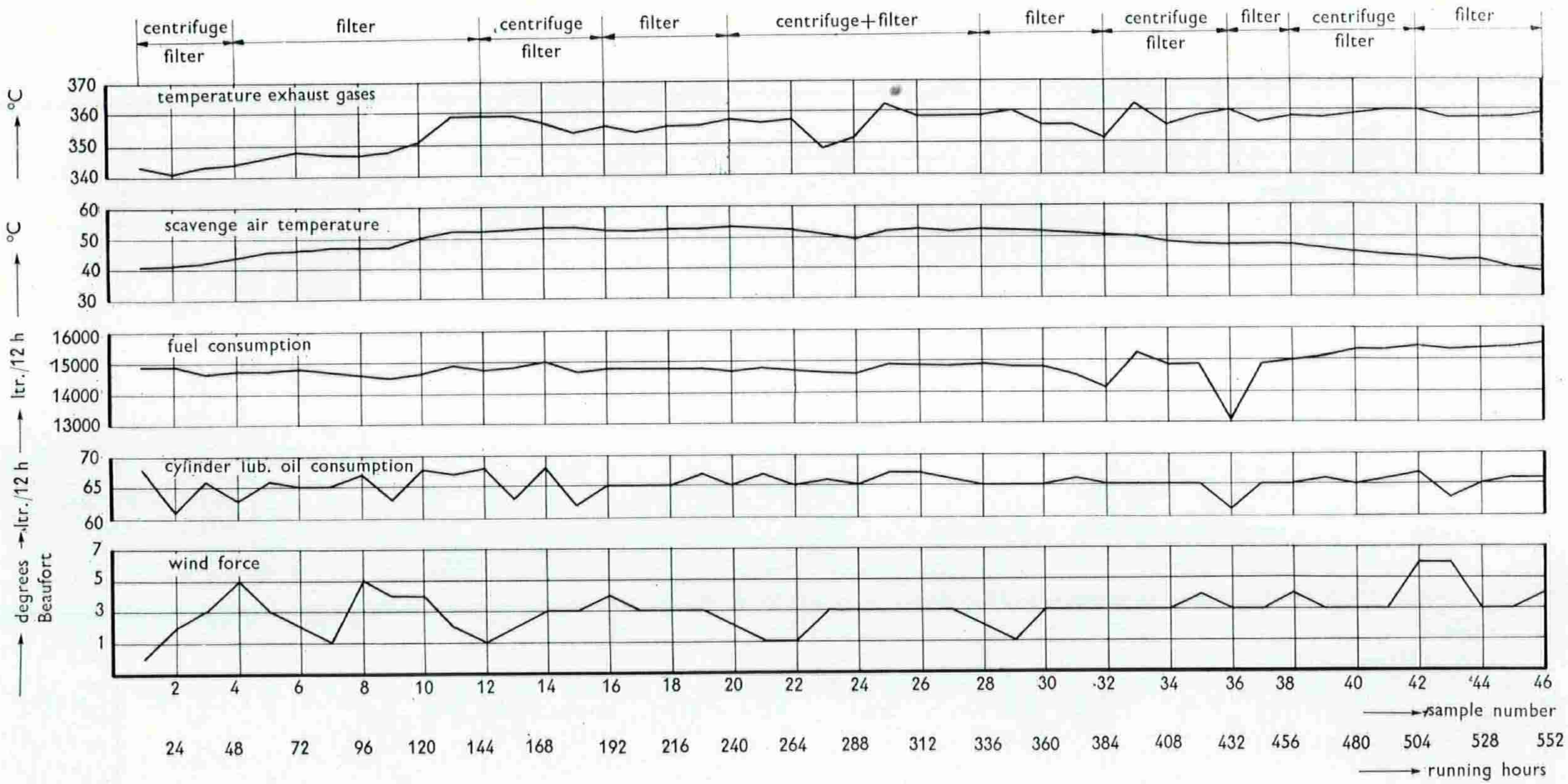

Fig. 2. Some service conditions during the third voyage of the m.s. „Algorab"

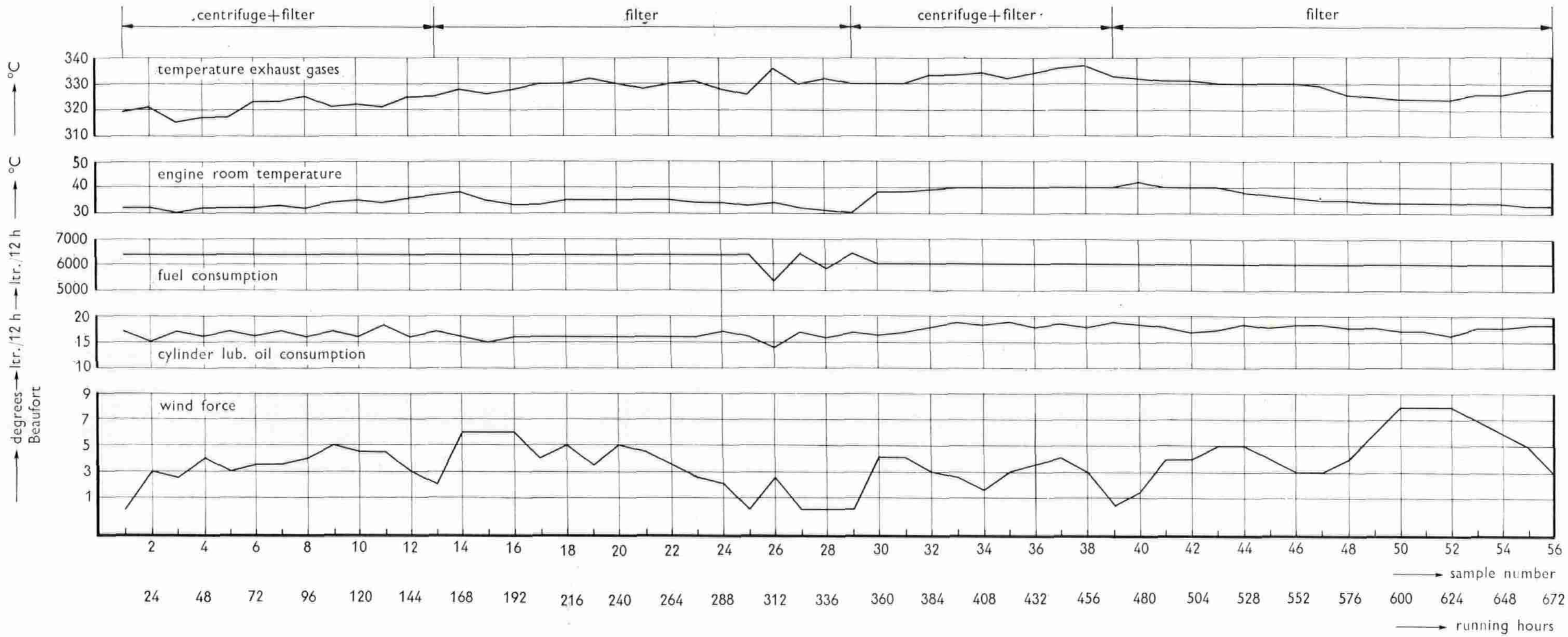

Fig. 3. Some service conditions during the two voyages of the m.s. ,,Congokust"

Table 2. Analyses of fuel samples taken during the first voyage of the m.s. „Algorab"

Test		Fuel treatment: Filter											
	Sample number →	B1	A1	B2	A2	B3	A3	B4	A4	B5	A5	B6	A6
Spec. gravity 60/60 °F													
Viscosity 100 °F cS		806											
(ASTM D445) Secs. Redw. I.		3300											
Conradson Carbon (ASTM D189)	%	9.5											
Sulphur (I.P. 63)	%	2.9											
Water (ASTM D95)	%	0.2		0.1	0.1	0.2		0.4	0.3	0.2	0.1	0.1	0.4
Ash (ASTM D482)	%	0.04		0.05	0.05	0.04		0.04	0.03	0.04	0.03	0.03	0.05
Asphalt (I.P. 143)	%	2.7		2.8	2.6	2.8		2.9	3.0	2.8	2.5	2.1	2.1
Unsolubles > 10 μ	ppm	25	21	53	46	27	25	26	19	20	16	19	24
Iron	ppm	10											
Sodium (ASTM D1318)	ppm	115											
Vanadium (ASTM D1548)	ppm	27											
Silicon (SiO_2)	ppm	14											

Table 3. Analyses of fuel samples taken during the second voyage of the m.s. „Algorab"

Test		Fuel treatment: Filter													
	Sample number →	B1	A1	B2	A2	B3	A3	B4	A4	B5	A5	B6	A6	B7	A7
Spec. gravity 60/60 °F		0.967													
Viscosity 100 °F cS		736													
(ASTM D445) Secs. Redw. I.		2990													
Conradson Carbon (ASTM D189)	%	8.9													
Sulphur (I.P. 63)	%	2.9													
Water (ASTM D95)	%	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.2
Ash (ASTM D482)	%	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03
Asphalt (I.P. 143)	%	2.2	2.1	2.3	2.1	2.4	2.1	2.3	2.2	2.2	2.1	2.1	2.0	2.2	2.1
Unsolubles > 10 μ	ppm	43	14	19	15	21	18	25	19	17	10	13	7	13	10
Iron	ppm	8													
Sodium (ASTM D1318)	ppm	70													
Vanadium (ASTM D1548)	ppm	40													
Silicon (SiO_2)	ppm	8													

Table 4. Analyses of fuel samples taken during the first voyage of the m.s. „Congokust"
B = Before treatment; A = After treatment

Test		Fuel treatment: Centrifuge + Filter								Fuel treatment: Filter							
	Sample number →	B1	A1	B2	A2	B3	A3	B4	A4	B5	A5	B6	A6	B7	A7	B8	A8
Spec. gravity 60/60 °F		0.970						0.956		0.949						0.952	
Viscosity 100 °F cS		342						365		345						302	
(ASTM D445) Secs. Redw. I		1400						1500		1410						1240	
Conradson Carbon (ASTM D189)	%	9.2						9.0		9.2						8.7	
Sulphur (I.P.63)	%	2.6						2.7		2.5						2.2	
Water (ASTM D95)	%	0.2	0.5	0.05	0.5	0.4	0.6	0.1	0.5	<0.05	0.05	0.05	0.1	0.05	0.1	0.05	0.1
Ash (ASTM D482)	%	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05	0.05	0.06	0.05
Asphalt (I.P.143)	%	2.6	3.0	2.4	3.0	2.3	2.8	2.8	3.0	2.8	2.8	3.1	3.1	3.2	3.3	3.6	3.6
Unsolubles > 10 μ	ppm	13	5	10	3	18	1	28	2	28	29	14	12	8	15	8	10
Iron	ppm	8						8		11						10	
Sodium (ASTM D1318)	ppm	50						50		55						55	
Vanadium (ASTM D1548)	ppm	45						50		50						160	
Silicon (SiO_2)	ppm	15						16		18						14	

Table 6. Analyses of fuel samples taken during the third voyage of the m.s. „Algorab"

Test	Sample number →	BC1	ACF1	BF2	AF2	BF3	AF3	BC4	ACF4	BF5	ACF5	BC6	ACF
Spec. gravity 60/60 °F		0.961											
Viscosity 100 °F cS		802											
(ASTM D445) Secs. Redw. I		3280											
Conradson Carbon (ASTM D189)	%	7.5											
Sulphur (I.P. 63)	%	3.0											
Water (ASTM D95)	%	0.2	0.3	<0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Ash (ASTM D482)	%	0.05	0.05	0.04	0.04	0.05	0.04	0.07	0.05	0.05	0.04	0.05	0.04
Asphalt (I.P. 143)	%	2.2	2.6	2.4	2.6	2.4	2.6	2.4	2.8	2.7	2.4	2.6	2.5
Unsolubles > 10 μ	ppm	34	14	28	27	22	17	58	1.5	16	14	49	7.4
Iron	ppm	13											
Sodium (ASTM D1318)	ppm	53											
Vanadium (ASTM D1548)	ppm	44											
Silicon (SiO_2)	ppm	14											

B = Before treatment; A = After treatment

37	A7	B8	A8	B9	A9	B10	A10	B11	A11	B12	A12
	Fuel treatment: Centrifuge + Filter										
70										687	
750										2820	
.8										9.2	
.2										3.0	
.7		0.6		0.4	0.2	0.2	0.8	0.5	0.7	0.5	
.04		0.05		0.05	0.02	0.03	0.03	0.04	0.02	0.03	
.9		2.6		2.3	2.0	2.3	2.2	2.0	2.2	2.0	
2	4.6	52	6.3	38	0.8	42	1.5	26	3.3	45	2.7
0										9	
0										95	
6										32	
8										9	

B = Before treatment; A = After treatment

8	A8	B9	A9	B10	A10	B11	A11	B12	A12	B13	A13	B14	A14
uel treatment: Centrifuge + Filter													
.970												0.970	
18												684	
920												2780	
.5												9.5	
.0												3.1	
.6	0.3	0.3	0.3	0.6	0.2	0.4	0.3	0.5	0.3	0.8	0.3	1.1	0.5
.03	0.03	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.03	0.03	0.03	0.04	0.03
.1	2.2	2.1	2.2	2.3	2.4	2.4	2.4	2.6	2.5	2.6	2.5	3.0	2.9
2	3.5	14	1.6	17	7	20	3.8	16	4.6	13	1.0	27	2.5
												10	
0												110	
0												65	
												10	

Table 5. Analyses of fuel samples taken during the second voyage of the m.s. ,,Congokust''
B = Before treatment; A = After treatment

Test	Sample number →	B1	A1	B2	A2	B3	A3	B4	A4	B5	A5	B6	A6	B7	A7	B8	A8
		Fuel treatment: Centrifuge+Filter								Fuel treatment: Filter							
Spec. gravity 60/60 °F		0.956				0.956		0.956								0.951	
Viscosity 100 °F cS		327				377		366								432	
(ASTM D445) Secs. Redw. I		1340				1550		1500								1770	
Conradson Carbon (ASTM D189)	%	8.8				8.4		10.1								10.5	
Sulphur (I.P.63)	%	2.4				2.5		2.2								2.4	
Water (ASTM D95)	%	0.2	0.9	0.2	0.8	0.2	0.7	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	<0.1	0.2
Ash (ASTM D482)	%	0.04	0.05	0.04	0.03	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03
Asphalt (I.P. 143)	%	4.5	4.6	4.1	4.2	4.4	4.4	5.2	4.4	5.4	5.3	4.8	4.2	4.4	4.2	4.2	4.6
Unsolubles $> 10\ \mu$	ppm	20	18	6	4	9	3	39	32	39	37	23	21	9	9	11	10
Iron	ppm	6				7		9								6	
Sodium (ASTM D1318)	ppm	55				45		65								60	
Vanadium (ASTM D1548)	ppm	14				8		15								8	
Silicon (SiO_2)	ppm	12				13		14								10	

C = Before Centrifuge+Filter ACF = After Centrifuge+Filter BF = Before Filter AF = After Filter

C7	ACF7	BF8	AF8	BC9	ACF9	BC10	ACF10	BF11	AF11
955		0.953						0.948	
01		411						413	
050		1680						1690	
8		8.3						8.3	
7		2.7						2.3	
5	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.1
04	0.04	0.04	0.05	0.04	0.03	0.04	0.04	0.07	0.06
4	2.4	2.4	2.9	3.0	2.9	3.0	3.5	2.3	3.2
0	13	12	13	26	5.5	21	11	27	28
3		7						5	
8		25						50	
0		45						135	
7		8						12	

b. *m.s. „Congokust"*

The oil emerging from the diaphragm separating the upper part of the crankcase from the cylinder was collected of every cylinder during 12 running hours of the engine.

After measuring the quantity and homogenizing a sample was taken. During the test periods of the two voyages the fuel was treated in accordance with the following scheme:

First voyage:	
from July 5th to July 11th 1967:	centrifuge + filter
from August 15th to August 23rd 1967:	filter
Second voyage:	
from September 10th to September 16th 1967:	centrifuge + filter
from November 2nd to November 11th 1967:	filter

The iron content of the samples was determined by the high sensitive röntgenfluorescence method.

2.2.2 Results

a. *m.s. „Algorab"*

The data obtained as described in the previous paragraph are given in Tables 7, 8 and 9.

b. *m.s. „Congokust"*

Tables 10 and 11 show the iron content of the drip oil and iron recovery per twelve running hours.

3 Statistical analysis of the results

The results of the measurements were analysed statistically. The statistical treatment of the data was performed with two wear rate measures being, the iron content and the iron recovery per twelve running hours.

The first mentioned measure was investigated for the first and second voyage of the m.s. „Algorab" since no data of iron recoveries were available.

Both wear rate measures were analysed in case of the third voyage of the m.s. „Algorab" and both voyages of the m.s. „Congokust".

In order to estimate the effect of the fuel treatment on the engine wear analyses of variance were carried out. In these analyses the following criteria were taken into account:

a. Fuel treatment.
b. Cylindereffect.
c. Period in which the results were obtained.
d. The interaction between fuel treatment and cylinder effect.

On the bases of the results of these analyses of variance it is possible to decide whether there exists a systematic difference in wear rate when either centrifuged or filtered residual fuel is used, correcting for the possibilities that the wear rate may depend on the cylinder under consideration (b), the recovery period (c) and on the interaction of cylindereffect and fuel treatment (d). Other factors influencing engine wear such as load variations occurrung under constant normal operating conditions have been assumed to be normally distributed (with zero mean and a variance which is independent of these factors). Moreover these factors were considered to be mutually independent.

The analyses were carried out for each cylinder and for every voyage separately.

The calculations concerning the data obtained during the first and second voyage of the m.s. „Algorab" and of both voyages of the m.s. „Congokust", include the following results.

1. Estimations of the wear rates S_f and S_c, in case filtered or centrifuged residual fuel was used respectively.
2. Estimations of difference S_f–S_c.
3. The 95% confidence intervals of S_f–S_c, determined by Scheffé's method.

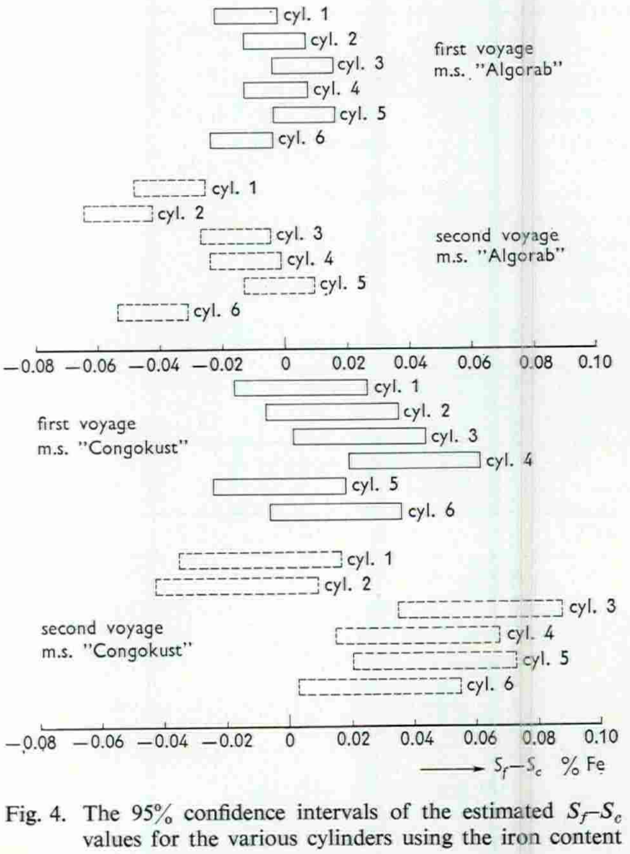

Fig. 4. The 95% confidence intervals of the estimated S_f–S_c values for the various cylinders using the iron content as the wear rate measure

Because the wear rates obtained from the third voyage of the m.s. „Algorab" appeared to be low in comparison with the random fluctuations the analysis of these data was carried out on the logarithm of the wear rate measures.

As a consequence of this logarithmic transformation the confidence intervals of S_f/S_c were calculated, in stead of the confidence intervals of S_f–S_c.

The estimated values of S_f, S_c and S_f–S_c as well as the 95% confidence intervals of S_f–S_c for each voyage and each cylinder for both wear rate measures are given in Tables 12 and 13.

The 95% confidence intervals of S_f–S_c and of S_f/S_c are shown in Figures 4, 5, 6 and 7.

4 Interpretation of the results

The figures reported in Tables 12 and 13 indicate:

1. Using the iron content of the drip oil for comparison of the wear rates occurring when centrifuged or filtered fuel is used, the results obtained from the first and third voyage of the m.s. „Algorab" and both voyages of the m.s. „Congokust" do not permit a conclusion in favour of one or the other fuel treatment.
2. The results obtained from the second voyage of the m.s. „Algorab" show a lower iron content of the drip oil when filtered fuel was used than when centrifuged fuel was used.
3. Using the total amount of collected iron for comparison, no significant wear rate difference occurs between the fuel treatments under consideration.
4. It has been proved that the engine cylinders do not behave similar as far as the wear rate is concerned when both wear rate measures are considered.
5. The effect of the fuel treatment on the wear rate is not independent of the cylinder under investigation. Some cylinders show better results with filtered fuel, while other show the opposite.

5 Discussion of the results

Interpretation 1, 3 and 5 of the foregoing chapter indicate that the differences of wear rates between the methods of fuel treatment must be due to factors affecting the wear rate, other than the fuel treatment.

Interpretation 2 might be explained by the fact that the engine, when burning centrifuged fuel was running under higher load conditions as is shown by the increase of fuel consumption and exhaust temperatures compared with those occurring during the filtered fuel period. Drydocking of the ship at the end of the return voyage showed that severe hull fouling had occurred between the two investigation periods of the voyage.

It should be born in mind that shipboard investigations under normal service conditions do not permit to create experimental laboratory outfit and running conditions of the engine nor the application of laboratory measuring methods.

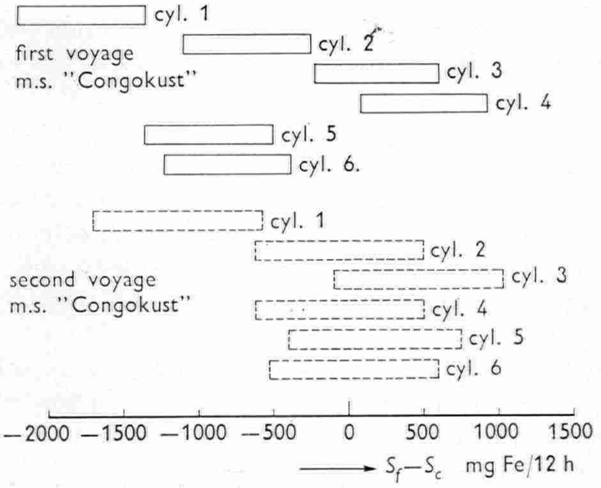

Fig. 5. The 95% confidence intervals of the estimated S_f–S_c values for the various cylinders using the iron recovery per twelve running hours as the wear rate measure

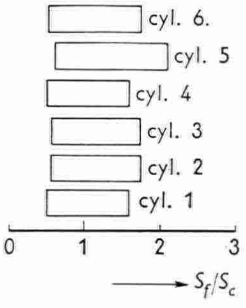

Fig. 6. The 95% confidence intervals of the estimated S_f/S_c values for the various cylinders during the third voyage of the m.s. „Algorab" using the iron content as the wear rate measure

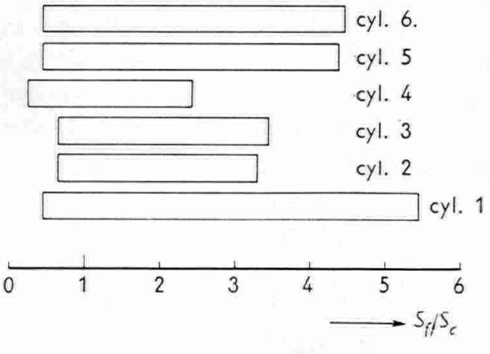

Fig. 7. The 95% confidence intervals of the estimated S_f/S_c values for the various cylinders during the third voyage of the m.s. „Algorab" using the iron recovery per twelve running hours as the wear rate measure

For instance building of circular gutters round the exposed outer ends of the cylinder liners, to collect the drip oil only, as were applied to the laboratory engine used in [13], was impossible.

Although the drip oil samples were taken during parts of the voyages where the engine was running under normal continuous load conditions, variations of these conditions could not be avoided completely. Moreover, contamination of the drip oil with crankcase lubricating oil carried along with the piston rod and loss of drip oil through the piston rod seals had to be accepted.

Because the quantities of cylinder drip oil and the relation between the quantity of contaminating crankcase oil and cylinder drip oil were considered to be constant, irrespective of random fluctuations, both the iron content of the oil recovered as well as the quantity of iron collected were used as measures for the wear rate.

Due to the method used it has unfortunately not been possible to determine the quantities of drip oil iron during the first and second voyage of the m.s. „Algorab".

If these data had also been available it would have been possible to compare both wear rate measures better.

6 Conclusions

1. The cylinder oil analysis applied is a simple method to obtain an indication of the wear rate of an engine cylinder by shortterm tests. The wear measurements as described in this report, could be carried out more accurately if the design of the engine permits a gutter round the exposed outer end of the cylinder. Contamination of the cylinder drip oil by crankcase lubricant could thus be avoided.
2. From the results obtained it may be concluded that no choice in favour of one of the two fuel treatments investigated can be made as far as cylinder liner and piston ring wear is concerned.
3. The analyses of the fuel samples indicate that centrifuging is somewhat more effective than filtering regarding the separation of unsolubles $> 10\ \mu$. However, the effect of the unsolubles in the fuel, after treatment, on the cylinder wear depends on the effectiveness of the injection equipment as a homogenizing device. Also regarding the water separation of the fuel the centrifuge method is more effective than the filters applied.
   In order to protect the fuel injection equipment the water content of the fuel has to be as low as possible.
4. Summarizing it may be concluded that the application of a reliable, simple and self-cleaning fuel filter with a mesh width of some 30–40 μ will not substantially affect the economically and technically justified performance of the main engine.

7 Future work

Laboratory experiments on an automatic selfcleaning filter with residual and blend fuels will be carried out.

Water separation by flash evaporation will be investigated. Proposals to investigate injection equipment wear are being made. Full scale tests on board with the treating equipment under development are prepared.

8 Acknowledgement

The Netherlands Ship Research Centre acknowledges the co-operation of Van Nievelt, Goudriaan & Co's Steamshipping Company Ltd. and the Royal Interocean Lines Ltd. which greatly facilitated the tests reported herein.

Also the work carried out by the Chief Engineers and their staffs is kindly acknowledged.

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Table 7. The iron content of the drip-oil samples obtained during the first voyage of the m.s. „Algorab".
Samples 1–22 were taken during the filter-period.
Samples 23–44 were taken during the centrifuge + filterperiod.

Sample number	Cylinder number 1	2	3	4	5	6
1	0.031	0.018	0.018	0.015	0.025	0.026
2	0.028	0.020	0.023	0.016	0.033	0.032
3	0.033	0.025	0.027	0.018	0.035	0.037
4	0.035	0.028	0.027	0.019	0.035	0.031
5	0.034	0.029	0.033	0.019	0.044	0.034
6	0.041	0.035	0.035	0.020	0.043	0.034
7	0.043	0.040	0.030	0.015	0.035	0.038
8	0.035	0.035	0.031	0.019	0.038	0.041
9	0.039	0.041	0.052	0.032	0.039	0.043
10	0.041	0.036	0.028	0.016	0.030	0.038
11	0.041	0.031	0.028	0.017	0.030	0.038
12	0.045	0.030	0.024	0.017	0.028	0.039
13	0.043	0.030	0.028	0.015	0.026	0.041
14	0.039	0.028	0.025	0.014	0.026	0.054
15	0.034	0.025	0.020	0.012	0.024	0.044
16	0.032	0.021	0.019	0.011	0.023	0.039
17	0.029	0.020	0.025	0.011	0.025	0.035
18	0.030	0.023	0.023	0.012	0.023	0.037
19	0.032	0.024	0.023	0.013	0.024	0.039
20	0.033	0.027	0.033	0.015	0.027	0.043
21	0.037	0.030	0.029	0.013	0.028	0.048
22	0.038	0.035	0.030	0.013	0.027	0.050
23	0.023	0.043	0.044	0.022	0.035	0.092
24	0.044	0.038	0.020	0.016	0.030	0.070
25	0.028	0.033	0.021	0.016	0.026	0.052
26	0.030	0.034	0.025	0.019	0.025	0.057
27	0.028	0.030	0.025	0.019	0.023	0.057
28	0.026	0.033	0.023	0.018	0.023	0.057
29	0.041	0.034	0.023	0.017	0.020	0.065
30	0.040	0.035	0.022	0.018	0.020	0.055
31	0.041	0.032	0.021	0.020	0.022	0.053
32	0.046	0.036	0.022	0.019	0.019	0.049
33	0.068	0.035	0.021	0.017	0.019	0.050
34	0.071	0.034	0.020	0.017	0.018	0.054
35	0.068	0.032	0.023	0.018	0.021	0.051
36	0.063	0.033	0.023	0.022	0.025	0.054
37	0.060	0.035	0.021	0.024	0.023	0.052
38	0.052	0.028	0.016	0.019	0.023	0.047
39	0.054	0.021	0.014	0.017	0.021	0.039
40	0.055	0.024	0.016	0.015	0.021	0.039
41	0.052	0.024	0.017	0.017	0.024	0.045
42	0.052	0.024	0.017	0.016	0.027	0.044
43	0.051	0.022	0.017	0.014	0.024	0.039
44	0.045	0.019	0.015	0.014	0.023	0.034

Table 8. The iron content of the drip-oil samples obtained during the second voyage of the m.s. „Algorab".
Samples 45–68 were taken during the filter-period.
Samples 69–92 were taken during the centrifuge + filterperiod.

Sample number	Cylinder number 1	2	3	4	5	6
45	0.042	0.048	0.019	0.018	0.022	0.033
46	0.034	0.070	*	0.012	0.020	0.036
47	0.041	0.050	0.022	0.017	0.025	0.037
48	0.040	0.054	0.025	0.013	0.026	0.037
49	0.040	0.060	0.025	0.015	0.022	0.038
50	0.030	0.057	0.021	0.015	0.024	0.039
51	0.031	0.050	0.020	0.014	0.022	0.033
52	0.036	0.047	0.022	0.015	0.022	0.033
53	0.041	0.055	0.032	0.021	0.028	0.038
54	0.045	0.051	0.026	0.018	0.023	0.035
55	0.037	0.043	0.024	0.015	0.020	0.037
56	0.034	0.043	0.019	0.015	0.020	0.035
57	0.031	0.036	0.016	0.015	0.018	0.035
58	0.027	0.034	0.017	0.015	0.020	0.038
59	0.025	0.032	0.016	0.015	0.020	0.036
60	0.026	0.030	0.017	0.016	0.020	0.039
61	0.039	0.031	0.019	0.016	0.020	0.027
62	0.025	0.031	0.018	0.021	0.039	0.015
63	0.048	0.048	0.035	0.018	0.036	0.049
64	0.038	0.037	0.027	0.018	0.028	0.044
65	0.046	0.037	0.028	0.017	0.024	0.043
66	0.037	0.034	0.027	0.018	0.025	0.049
67	0.037	0.036	0.028	0.018	0.028	0.051
68	0.035	0.024	0.037	0.018	0.026	0.051
69	0.041	0.056	0.043	0.030	0.026	0.062
70	0.044	0.081	0.041	0.030	0.028	0.092
71	0.050	0.082	0.038	0.023	0.029	0.088
72	0.058	0.087	0.035	0.024	0.030	0.086
73	0.060	0.089	0.036	0.028	0.031	0.089
74	0.065	0.094	0.036	0.027	0.028	0.095
75	0.067	0.095	0.042	0.027	0.028	0.081
76	0.080	0.099	0.042	0.025	0.025	0.107
77	0.075	0.096	0.036	0.027	0.024	0.091
78	0.077	0.099	0.041	0.026	0.028	0.079
79	0.070	0.098	0.045	0.032	0.025	0.076
80	0.072	0.106	0.047	0.035	0.024	0.071
81	0.103	0.112	0.042	0.035	0.024	0.065
82	0.094	0.101	0.046	0.031	0.024	0.060
83	0.074	0.101	0.040	0.030	0.022	0.063
84	0.076	0.099	0.045	0.028	0.026	0.068
85	0.079	0.101	0.035	0.026	0.026	0.061
86	0.085	0.104	0.041	0.030	0.029	0.068
87	0.072	0.103	0.037	0.026	0.025	0.071
88	0.088	0.093	0.043	0.037	0.024	0.098
89	0.080	0.105	0.038	0.031	0.023	0.093
90	0.085	0.106	0.027	0.028	0.024	0.089
91	0.075	0.096	0.025	0.025	0.026	0.087
92	0.071	0.108	0.036	0.029	0.023	0.088

* Could not be analysed due to heavy pollution.

Table 9. The iron content of the drip-oil samples and iron recovery per twelve running hours obtained during the third voyage of the m.s. „Algorab"

Fuel treatment	Sample number	Cylinder number 1 drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	2 drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	3 drip-oil rec. g/12 h	iron content	iron rec. mg/12 h
Centrifuge +filter	1	785.7	0.05	392.85	7103.0	0.02	1420.6	1831.0	0.01	183.1
	2	1948.5	0.04	779.40	4148.0	0.02	829.6	1516.0	0.02	303.2
	3	4902.7	0.02	980.54	2852.0	0.02	570.4	2066.0	0.02	413.2
	4	33360.0	0.02	6672.0	3724.0	0.02	744.8	1564.0	0.02	312.8
Filter	5	29330.0	0.02	5866.0	4667.0	0.02	933.4	2577.0	0.02	515.4
	6	25865.0	0.02	5173.0	3952.0	0.03	1185.6	2145.0	0.02	429.0
	7	18503.0	0.02	3700.6	4659.0	0.02	931.8	1870.0	0.02	374.0
	8	28285.0	0.02	5657.0	6128.0	0.02	1225.6	4518.0	0.02	903.6
Filter	9	17364.0	0.02	3472.8	3536.0	0.03	1060.8	2247.0	0.02	449.4
	10	27798.0	0.02	5559.6	2106.0	0.03	631.8	4675.0	0.02	935.0
	11	28026.0	0.02	5605.2	2043.0	0.03	612.9	3669.0	0.02	733.8
	12	32010.0	0.02	6402.0	3708.0	0.02	741.6	3496.0	0.02	699.2
Centrifuge +filter	13	37659.0	0.02	7531.8	4070.0	0.02	814.0	4973.0	0.02	944.6
	14	32386.0	0.02	6477.2	3237.0	0.03	971.1	7016.0	0.02	1403.2
	15	18700.0	0.02	3740.0	1862.0	0.04	744.8	5131.0	0.02	1026.2
	16	24891.0	0.02	4978.2	1618.0	0.04	647.2	7228.0	0.02	1445.6
Filter	17	20428.0	0.02	4085.6	998.0	0.05	499.0	8046.0	0.02	1609.2
	18	31978.0	0.02	6395.6	919.0	0.04	367.6	6600.0	0.02	1320.0
	19	45351.0	0.02	9070.2	825.0	0.06	495.0	5822.0	0.02	1164.4
	20	36284.0	0.02	7256.8	1422.0	0.06	853.2	5461.0	0.02	1092.2
Centrifuge +filter	21	27091.0	0.02	5418.2	1744.0	0.05	872.0	4895.0	0.02	979.0
	22	17411.0	0.02	3482.2	2475.0	0.03	742.5	5948.0	0.02	1189.6
	23	17537.0	0.02	3507.4	5940.0	0.02	1188.0	7166.0	0.02	1433.2
	24	16083.0	0.02	3216.6	1328.0	0.03	398.4	7103.0	0.02	1420.6
Centrifuge +filter	25	126.0	0.08	100.8	220.0	0.12	264.0	699.0	0.04	279.6
	26	165.0	0.09	148.5	369.0	0.10	369.0	762.0	0.03	228.6
	27	141.0	0.08	112.8	338.0	0.12	371.8	723.0	0.03	216.9
	28	188.0	0.08	150.4	361.0	0.10	361.0	628.0	0.03	188.4
Filter	29	220.0	0.08	176.0	314.0	0.10	314.0	754.0	0.03	226.2
	30	322.0	0.09	289.8	526.0	0.10	526.0	1006.0	0.03	301.8
	31	361.0	0.10	361.0	723.0	0.11	795.3	1454.0	0.03	436.2
	32	471.0	0.09	423.9	731.0	0.10	731.0	1469.0	0.02	293.8
Centrifuge +filter	33	291.0	0.08	232.8	691.0	0.09	621.9	1202.0	0.03	360.6
	34	574.0	0.09	516.6	629.0	0.09	566.1	990.0	0.03	297.0
	35	448.0	0.08	358.4	534.0	0.10	534.0	1398.0	0.03	419.4
	36	518.0	0.08	414.4	629.0	0.10	629.0	1438.0	0.02	287.6
Filter	37	479.0	0.08	383.2	731.0	0.20	1462.0	1406.0	0.02	281.2
	38	401.0	0.07	280.7	574.0	0.09	516.6	1257.0	0.02	251.4
Centrifuge +filter	39	220.0	0.08	176.0	762.0	0.08	609.6	1571.0	0.02	314.2
	40	220.0	0.02	44.0	550.0	0.08	440.0	2224.0	0.02	444.8
	41	259.0	0.09	233.1	542.0	0.08	433.6	1587.0	0.02	317.4
	42	204.0	0.09	183.6	613.0	0.08	490.4	1076.0	0.02	215.2
Filter	43	346.0	0.08	276.8	322.0	0.08	257.6	2412.0	0.02	482.4
	44	330.0	0.09	297.0	1100.0	0.08	880.0	1556.0	0.02	311.2
	45	220.0	0.13	286.0	707.0	0.08	565.6	1155.0	0.02	231.0
	46	126.0	0.08	75.6	684.0	0.07	478.8	1249.0	0.02	249.8

Cylinder number								
4			5			6		
drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h
1359.0	0.02	271.8	1571.0	0.03	471.3	408.0	0.04	163.2
1540.0	0.02	308.0	10080.0	0.03	3024.0	416.0	0.05	208.0
1823.0	0.02	364.6	7244.0	0.03	2173.2	636.0	0.05	318.0
1830.0	0.02	366.0	7440.0	0.03	2232.0	550.0	0.06	330.0
1807.0	0.02	361.4	10112.0	0.03	3033.6	298.0	0.06	178.8
1021.0	0.02	204.2	11487.0	0.02	2297.4	228.0	0.06	136.8
1336.0	0.02	267.2	9743.0	0.07	6820.1	306.0	0.03	91.8
1155.0	0.02	231.0	13985.0	0.02	2797.0	872.0	0.08	697.6
2004.0	0.02	400.8	15085.0	0.02	3017.0	566.0	0.06	339.6
1948.0	0.02	389.6	29087.0	0.02	5817.4	330.0	0.06	198.0
1414.0	0.02	282.8	18040.0	0.02	3608.0	298.0	0.05	149.0
2310.0	0.02	462.0	27908.0	0.02	5581.6	456.0	0.05	228.0
1988.0	0.02	397.6	19273.0	0.02	3854.6	401.0	0.05	200.5
1909.0	0.02	381.8	10065.0	0.02	2013.0	244.0	0.05	122.0
2923.0	0.02	584.6	20900.0	0.02	4180.0	236.0	0.05	118.0
1901.0	0.02	380.2	18071.0	0.02	3614.2	165.0	0.06	99.0
2828.0	0.02	565.6	14944.0	0.02	2988.8	204.0	0.06	183.6
1823.0	0.04	729.2	17285.0	0.02	3457.0	196.0	0.06	117.6
1838.0	0.02	367.6	11432.0	0.02	2286.4	267.0	0.06	160.2
2121.0	0.02	424.2	29173.0	0.02	5834.6	189.0	0.06	113.4
1956.0	0.02	391.2	34076.0	0.02	6815.2	173.0	0.06	103.8
1870.0	0.02	374.0	23162.0	0.02	4632.4	141.0	0.07	98.7
1776.0	0.02	355.2	9358.0	0.02	1871.6	181.0	0.07	126.7
1815.0	0.02	363.0	20365.0	0.02	4073.0	157.0	0.07	109.9
2828.0	0.03	848.4	251.0	0.16	401.6	23.6	0.10	23.6
2192.0	0.02	438.4	267.0	0.03	80.1	70.7	0.11	77.7
2663.0	0.02	532.6	298.0	0.35	1043.0	86.4	0.07	60.5
3928.0	0.02	785.6	754.0	0.23	1734.2	361.0	0.12	433.2
2695.0	0.02	539.0	1626.0	0.09	1463.4	338.0	0.11	371.8
1351.0	0.02	270.2	3968.0	0.08	3174.4	291.0	0.10	291.0
3944.0	0.03	1183.2	2978.0	0.11	3275.8	471.0	0.05	235.5
3528.0	0.03	1058.2	2271.0	0.05	1135.5	448.0	0.09	403.2
3316.0	0.03	994.8	1697.0	0.05	848.5	291.0	0.09	261.9
3127.0	0.04	1250.9	880.0	0.06	528.0	236.0	0.10	236.0
2608.0	0.03	782.4	1163.0	0.06	697.8	275.0	0.09	247.5
2695.0	0.02	539.0	1163.0	0.06	697.8	354.0	0.06	212.4
2176.0	0.02	435.2	1422.0	0.02	284.4	220.0	0.08	176.0
2577.0	0.03	773.1	1524.0	0.02	304.8	165.0	0.09	148.5
1791.0	0.02	358.2	432.0	0.06	379.2	291.0	0.09	261.9
1328.0	0.03	398.4	526.0	0.07	368.2	157.0	0.09	141.3
2051.0	0.02	410.2	574.0	0.08	459.2	236.0	0.09	212.4
2255.0	–	–	519.0	0.09	467.1	338.0	0.08	270.4
2766.0	0.02	553.2	770.0	0.08	616.0	526.0	0.08	420.8
2318.0	0.02	463.6	1021.0	0.08	816.8	534.0	0.09	480.6
888.0	0.02	177.6	550.0	0.12	660.0	416.0	0.09	374.4
613.0	0.02	122.6	440.0	0.07	308.0	236.0	0.08	188.8

Table 10. The iron content of the drip-oil samples and iron recovery per twelve running hours obtained during the first voyage of the m.s. „Congokust"

		Cylinder number								
		1			2			3		
Fuel treatment	Sample number	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h
Centrifuge +filter	1	1780	0.10	1780	1140	0.07	798	410	0.11	451
	2	2270	0.11	2497	1440	0.07	1008	310	0.10	310
	3	2390	0.12	2868	1350	0.09	1215	410	0.09	369
	4	2540	0.16	4064	1370	0.08	1096	530	0.08	424
	5	2270	0.15	3405	1540	0.09	1386	390	0.08	312
	6	2180	0.15	3270	1180	0.08	944	340	0.08	272
	7	2220	0.12	2664	1320	0.08	1056	550	0.08	440
	8	2020	0.12	2424	1540	0.07	1078	440	0.08	352
	9	1900	0.11	2090	1320	0.08	1056	480	0.08	384
	10	2200	0.12	2640	1300	0.07	910	610	0.09	549
	11	1710	0.12	2052	1160	0.10	1160	310	0.08	248
	12	2120	0.09	1908	1370	0.07	959	240	0.12	288
	13	1760	0.12	2112	1200	0.07	840	370	0.08	296
Filter	14	750	0.17	1275	600	0.15	900	430	0.15	645
	15	460	0.15	690	510	0.13	663	430	0.15	645
	16	870	0.15	1305	540	0.13	702	550	0.13	715
	17	490	0.14	686	370	0.12	444	310	0.12	372
	18	680	0.14	952	300	0.08	240	670	0.11	737
	19	360	0.11	396	340	0.09	306	600	0.12	720
	20	320	0.13	416	370	0.09	333	650	0.11	715
	21	900	0.13	1170	200	0.08	160	800	0.09	720
	22	490	0.14	686	410	0.08	328	360	0.08	288
	23	660	0.13	858	250	0.09	225	290	0.11	319
	24	440	0.11	484	390	0.07	273	360	0.07	252
	25	700	0.10	700	340	0.07	238	240	0.07	168
	26	730	0.10	730	320	0.08	256	150	0.07	105
	27	610	0.10	610	410	0.08	328	400	0.08	320
	28	1170	0.12	1404	240	0.07	168	400	0.18	720
	29	560	0.11	616	260	0.08	208	840	0.15	1260

Table 11. The iron content of the drip-oil samples and iron recovery per twelve running hours obtained during the second voyage of the m.s. „Congokust"

		Cylinder number								
		1			2			3		
Fuel treatment	Sample number	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h
Centrifuge +filter	1	1170	0.12	1404	960	0.27	2592	1080	0.07	756
	2	1160	0.14	1624	1440	0.15	2160	290	0.06	174
	3	1540	0.17	2618	1180	0.19	1770	320	0.06	192
	4	1340	0.15	2010	960	0.15	1440	220	0.07	154
	5	1460	0.16	2336	1210	0.18	2178	290	0.07	203
	6	820	0.15	1230	850	0.16	1360	550	0.08	440
	7	1340	0.15	2010	900	0.18	1620	270	0.08	216
	8	780	0.14	1092	1000	0.18	1800	430	0.09	387
	9	1240	0.13	1612	1040	0.16	1664	300	0.08	240
	10	1170	0.15	1755	1160	0.18	2088	360	0.08	288
Filter	11	360	0.13	468	1060	0.21	2226	680	0.19	1292
	12	360	0.15	540	960	0.21	2016	530	0.15	795
	13	390	0.13	507	1250	0.19	2375	680	0.16	1088
	14	420	0.13	546	970	0.19	1843	260	0.13	338
	15	490	0.13	637	990	0.21	2079	650	0.13	845
	16	490	0.13	637	750	0.20	1500	550	0.15	825
	17	560	0.15	840	960	0.19	1824	670	0.14	938
	18	240	0.12	288	1020	0.16	1632	610	0.13	793
	19	360	0.13	468	960	0.17	1632	430	0.13	559
	20	490	0.14	686	1040	0.16	1664	580	0.13	754
	21	820	0.14	1148	1000	0.14	1400	600	0.12	720
	22	420	0.14	588	1200	0.13	1560	320	0.11	352
	23	440	0.13	572	1710	0.11	1881	1020	0.12	1224
	24	360	0.14	504	1370	0.12	1644	430	0.13	559
	25	560	0.15	840	1420	0.11	1562	1020	0.13	1326
	26	510	0.15	765	1470	0.15	2205	370	0.13	481
	27	490	0.14	686	1250	0.13	1625	190	0.12	228

Cylinder number								
4			5			6		
drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h
1770	0.12	2124	1530	0.11	1683	2040	0.07	1428
1930	0.10	1930	1420	0.11	1562	1950	0.06	1170
1970	0.09	1773	1420	0.11	1562	1930	0.06	1158
1530	0.09	1377	2000	0.12	2400	2180	0.08	1744
1620	0.09	1458	1550	0.11	1705	2440	0.06	1464
1690	0.09	1521	1600	0.10	1600	2110	0.06	1266
1550	0.09	1395	1150	0.10	1150	2080	0.08	1664
1400	0.09	1260	2060	0.10	2060	2180	0.07	1526
1800	0.08	1440	1370	0.09	1233	2110	0.06	1266
1200	0.10	1200	1220	0.10	1220	2080	0.06	1248
1400	0.09	1260	1800	0.10	1800	2380	0.09	2142
1080	0.08	864	1930	0.09	1737	2150	0.06	1290
1280	0.08	1024	1660	0.10	1660	2260	0.06	1356
1060	0.19	2014	240	0.18	432	600	0.11	660
1100	0.21	2310	400	0.16	640	840	0.11	924
620	0.19	1178	480	0.14	672	660	0.10	660
860	0.16	1376	900	0.13	1170	880	0.09	792
1930	0.13	2509	610	0.11	671	1220	0.07	854
1680	0.12	2016	420	0.13	546	950	0.07	665
2150	0.12	2580	1060	0.07	742	620	0.10	620
1930	0.12	2316	1100	0.09	990	1060	0.07	742
1530	0.11	1683	1480	0.08	1184	710	0.07	497
1370	0.11	1507	1100	0.08	880	640	0.07	448
1750	0.11	1925	1330	0.07	931	880	0.07	616
1930	0.10	1930	900	0.07	630	840	0.07	588
1550	0.13	2015	1130	0.07	791	770	0.08	616
1930	0.11	2123	510	0.08	408	660	0.09	594
1730	0.10	1730	600	0.08	480	510	0.08	408
1600	0.11	1760	510	0.07	357	600	0.07	420

Cylinder number								
4			5			6		
drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h	drip-oil rec. g/12 h	iron content	iron rec. mg/12 h
2130	0.09	1917	730	0.09	657	1770	0.07	1239
2060	0.09	1854	490	0.08	392	1100	0.07	770
1750	0.10	1750	930	0.09	837	2240	0.06	1344
1730	0.10	1730	690	0.09	621	1530	0.06	918
1570	0.10	1570	1150	0.09	1035	2060	0.05	1030
1320	0.12	1584	1100	0.09	990	840	0.04	336
2260	0.11	2486	990	0.09	891	2240	0.05	1120
1930	0.11	2123	930	0.08	744	1040	0.09	936
1570	0.11	1727	930	0.08	744	1600	0.08	1280
1930	0.12	2316	880	0.09	792	1600	0.07	1120
1170	0.18	2106	840	0.14	1176	1100	0.12	1320
1100	0.20	2200	730	0.13	949	900	0.11	990
2220	0.17	3774	660	0.13	858	1510	0.10	1510
240	0.16	348	380	0.13	494	1460	0.09	1314
750	0.18	1350	490	0.13	637	1300	0.09	1170
1220	0.18	2196	1330	0.13	1729	1550	0.10	1550
2060	0.17	3502	1260	0.14	1764	1770	0.09	1593
1480	0.15	2220	380	0.14	532	990	0.09	891
1240	0.16	1984	660	0.13	858	1220	0.09	1098
750	0.14	1050	840	0.12	1008	750	0.08	600
1280	0.12	1536	840	0.12	1008	800	0.08	640
750	0.11	825	400	0.12	480	1100	0.09	990
3060	0.11	3366	820	0.12	984	860	0.09	774
600	0.11	660	770	0.13	1001	750	0.09	675
1260	0.11	1386	840	0.16	1344	990	0.09	891
1330	0.12	1596	600	0.16	960	880	0.09	792
1040	0.12	1248	240	0.14	336	1060	0.09	954

Table 12. Results of the statistical analysis using the iron content of the drip-oil samples as the wear rate measure. a_{95} and b_{95} are the lower and upper limit of the 95% confidence intervals of S_f–S_c and of S_f/S_c respectively.

Voyage	Cylinder number	S_f	S_c	S_f–S_c	a_{95}	b_{95}
First voyage of the m.s. ,,Algorab"	1	0.0360	0.0472	−0.0112	−0.0211	−0.0013
	2	0.0287	0.0309	−0.0022	−0.0121	0.0077
	3	0.0278	0.0212	0.0066	−0.0033	0.0165
	4	0.0160	0.0179	−0.0019	−0.0118	0.0080
	5	0.0304	0.0233	0.0071	−0.0028	0.0170
	6	0.0392	0.0524	−0.0132	−0.0231	−0.0033
Second voyage of the m.s. ,,Algorab"	1	0.0360	0.0725	−0.0365	−0.0477	−0.0253
	2	0.0432	0.0963	−0.0531	−0.0643	−0.0419
	3	0.0235	0.0390	−0.0155	−0.0267	−0.0043
	4	0.0164	0.0288	−0.0124	−0.0236	−0.0012
	5	0.0241	0.0259	−0.0018	−0.0130	0.0094
	6	0.0378	0.0801	−0.0423	−0.0535	−0.0311
First voyage of the m.s. ,,Congokust"	1	0.1269	0.1223	0.0046	−0.0166	0.0258
	2	0.0931	0.0785	0.0146	−0.0066	0.0358
	3	0.1119	0.0885	0.0234	0.0022	0.0446
	4	0.1325	0.0915	0.0410	0.0198	0.0622
	5	0.1006	0.1031	−0.0025	−0.0237	0.0187
	6	0.0825	0.0669	0.0156	−0.0056	0.0368
Second voyage of the m.s. ,,Congokust"	1	0.1371	0.1460	−0.0089	−0.0350	0.0172
	2	0.1635	0.1800	−0.0165	−0.0426	0.0096
	3	0.1353	0.0740	0.0613	0.0352	0.0874
	4	0.1465	0.1050	0.0415	0.0154	0.0676
	5	0.1335	0.0870	0.0465	0.0204	0.0726
	6	0.0929	0.0640	0.0289	0.0028	0.0550
		S_f	S_c	S_f–S_c	$a_{95}(S_f/S_c)$	$b_{95}(S_f/S_c)$
Third voyage of the m.s. ,,Algorab"	1	0.0356	0.0399	−0.0043	0.51	1.57
	2	0.0493	0.0498	−0.0005	0.56	1.75
	3	0.0212	0.0216	−0.0004	0.55	1.73
	4	0.0210	0.0234	−0.0024	0.51	1.58
	5	0.0404	0.0362	0.0042	0.60	2.07
	6	0.0685	0.0700	−0.0015	0.55	1.73

Table 13. Results of the statistical analysis using the iron recovery per twelve running hours as the wear rate measure. a_{95} and b_{95} are the lower and upper limit of the 95% confidence intervals of S_f–S_c and of S_f/S_c respectively.

Voyage	Cylinder number	S_f	S_c	S_f–S_c	a_{95}	b_{95}
First voyage of the m.s. ,,Congokust"	1	811	2598	−1787	−2207	−1367
	2	361	1039	− 678	−1099	− 258
	3	544	355	189	− 232	609
	4	1936	1433	503	83	924
	5	720	1644	− 924	−1344	− 503
	6	632	1440	− 809	−1229	− 388
Second voyage of the m.s. ,,Congokust"	1	631	1769	−1139	−1708	− 570
	2	1804	1867	63	− 632	506
	3	772	305	467	− 102	1035
	4	1846	1906	− 60	− 628	509
	5	948	770	178	− 391	746
	6	1044	1009	35	− 534	604
		S_f	S_c	S_f–S_c	$a_{95}(S_f/S_c)$	$b_{95}(S_f/S_c)$
Third voyage of the m.s. ,,Algorab"	1	1292	738	555	0.56	5.45
	2	643	609	35	0.34	3.29
	3	508	458	50	0.36	3.45
	4	394	506	− 112	0.25	2.42
	5	1921	1364	557	0.45	4.38
	6	233	163	70	0.46	4.45

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