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Investigations into Abrasive and Corrosive wear mechanisms of Pistons and Liners in large bore 2-stroke diesel engine cylinders

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Abstract: The simultaneous collection of Cylinder Drain Oil (CDO) and Engine Performance Data is used to construct possible models and mechanisms for cylinder wear observed in large-bore 2-stroke diesel engines. The focus of the study is three 12 cylinder MAN B&W K90MC engines installed in modern container ships. Measurement of Iron ppm in the CDO is used to assess the degree of cylinder wear, which is seen to be continuously fluctuating as a consequence of variations in combustion conditions and deposit formations on the pistons. The study indicates that combustion conditions and deposit formations are the predominant cause of wear. On the other hand sulphur content of the fuel, and variations in sulphur, are noted to have less influence on wear, and less than generally understood to be the case.

INTRODUCTION

A project to study the MAN B&W K90MC engines of three container ships using regular sampling of Cylinder lubricant Drain Oil (CDO) and simultaneous collection of engine performance data was commenced in October 2002. The objective of the trial was to study ring groove wear and is the subject of the paper "Development of wear-resistant piston ring groove designs for large two-stroke engines" [1].

The interpretation of the collected data from the trial provided insight into combustion, lubrication and engine operating conditions.

The first part of the paper summarises procedures employed and summarises findings in respect of engine settings, power measurement, operating conditions and maintenance.

The second part interprets data from simultaneous sampling of CDO and recording of engine performance. New information about wear mechanisms of the liners of the 2-stroke marine diesel engine are discussed, and the frequency of incidence of the different mechanisms is evaluated.

Evidence is demonstrated to indicate that the most frequent cause of higher than normal wear is due to variations in combustion conditions rather than acid corrosion caused by Sulphur in the fuel.

Procedures for sampling of Cylinder Drain Oil (CDO) and collection of Engine Performance data from three container ship engines

Flame Marine Limited was engaged by MAN B&W in 2002 to organize the collection of fuel and lubricant samples and engine performance data from the MAN B&W 12 cylinder K90MC main engines of three sister container ships, built in 2000, which operate between Japan and North Europe, lifting fuel in both Rotterdam and Singapore.

One set of fuel and CDO samples, and one set of engine performance data were to be collected every 15 days (300 to 360 operating hours). Cylinder drain oil analysis procedures and diagnostic methods have been developed by Flame Marine since 1998, but required adjustment to fulfill the specific research objective of MAN B&W into ring groove wear. It was hoped that the diagnostic procedures would provide a more rapid means of checking incidence of ring groove wear than conventional methods using physical inspections and calibration.

The procedures used to investigate piston and cylinder conditions are elaborated.

Cylinder Drain Oil (CDO) Sampling

Collection of CDO samples and recording of performance data from three ships commenced on the following dates:

Ship A – 17th November 2002

Ship B – 24th February 2003

Ship C – 24th March 2003

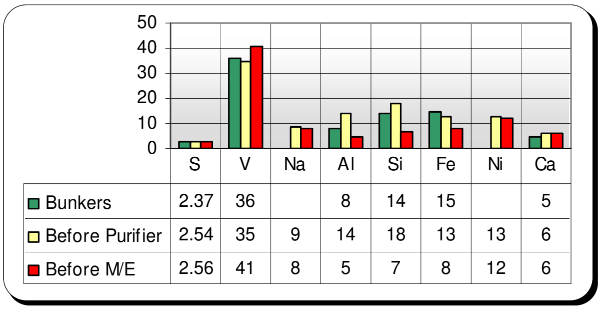
The objective of the study was to investigate wear of the piston ring grooves by measuring the amount of wear debris in cylinder drain oil samples. The findings are reported separately [1].

Fuel Sampling

It was expected that the presence of cat-fines in the fuel would influence ring groove wear. To assess the amount of cat-fine material injected into the engine one sample of fuel was taken before main engine fuel purifier and one sample before main engine fuel pump.

Comparison of the "fuel as delivered" with the fuel "before purifier" would show the reduction of cat-fines precipitated or filtered out before arriving at the purifier. Analysis of the fuel sampled before main engine pump would show the amount by which cat-fines are reduced as a result of centrifugal separation and filtration, and indicate the amount being injected into the engine.

The three fuel analyses, "as Delivered", "before Purifier" and "before ME pump" also showed variations in other characteristics of the fuel, indicating variations in Sulphur and Vanadium and other components. (Chart 1) The variations are explained by the fact that residual marine fuels are not homogeneous and that the analysis of fuel "as Delivered" is an average of the total quantity of fuel delivered. The fuel which is being injected into the combustion chamber is continuously changing. It was therefore important to have the Sulphur and Vanadium values for the fuel at the time that the cylinder oil drain samples were being drawn.



	S	V	Na	Al	Si	Fe	Ni	Ca
🟩 Bunkers	2.37	36		8	14	15		5
🟨 Before Purifier	2.54	35	9	14	18	13	13	6
🟥 Before M/E	2.56	41	8	5	7	8	12	6

Fuel Analysis Comparison

Chart 1 – Ship A (6th July 03 samples)

Performance measurement

It was expected that the power output of each cylinder, overall engine power, pressures and temperatures would influence ring wear and possibly also influence ring groove wear.

Cylinder pressure and combustion parameters for each cylinder are measured by Electronic Diesel Analyser (EDA). The data provided by the EDA proved valuable, when correctly set, but some of the data output, Mean Indicated Pressure (MIP) and Angle of Ignition in particular, was unreliable. Attempts were made to rectify or limit the errors with assistance of ships staff and the suppliers of the EDA equipment over the period of the study.

The Cylinder Lubricant

To understand the significance of the changes seen in the cylinder lubricant drain analyses, new cylinder lubricant was also regularly sampled. Previous experience had shown that the compounding of the cylinder lubricants supplied can vary considerably from one delivery to the next. A sample of fresh lubricating oil was therefore drawn from the lubricator supply line simultaneously with the used cylinder lubricant and fuel samples.

Throughout the trials lubricant feed was controlled within the range of 1.00 to 1.25 g/kWh by load dependent actuator.

Test Procedure

Engine performance data, and fuel and drain oil samples are collected whilst operating at normal operating power between 75% and 95% MCR. The bunker analysis report, fuel and CDO samples and engine performance data are landed at the next port and forwarded by courier to the analytical laboratory.

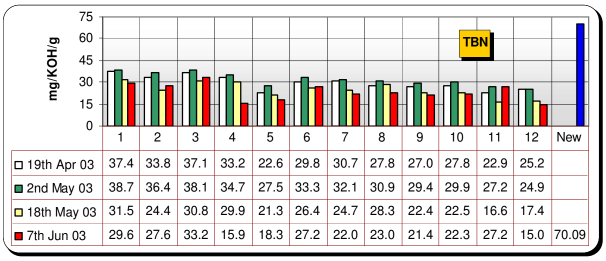
Results of the fuel and drain oil analyses are studied to evaluate combustion and lubrication conditions in each cylinder unit. The findings are then correlated with the engine pressures and temperatures, and with engine settings. Interpretation of the results provides information on engine operating conditions and pointers to variations in conditions of operation.

The recorded engine power and main operating parameters are compared with the Shop Test Performance data (Table 1)

	Red – Higher **Blue** – Lower	**Performance Curve (84.5 % MCR)**	**Measured Average**
RPM	rpm	89	**92.3**
Fuel Rack	mm	113	**113.6**
Pcom	Kg/cm^2	105	**99.7**
Pmax	Kg/cm^2	140	**130.3**
Pmax-Pcom	Kg/cm^2	35	**30.6**
MIP	Kg/cm^2	16.1	16.1
T/C rev	rpm	9,800	**9,682**
Pscav	Kg/cm^2	2.0	**2.1**

Table 1- Comparison with Shop Test Data

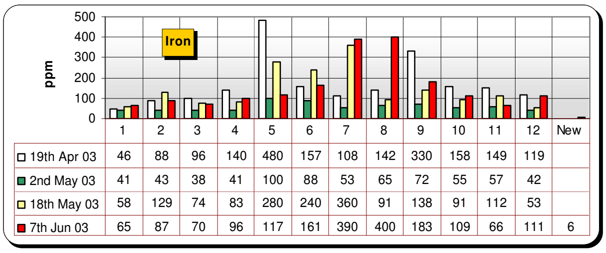
The lubricant consumption and effective power, both as recorded at the time of sampling of the CDO, are used to calculate the overall cylinder lubricant feed rate for the engine and for each cylinder unit.



	1	2	3	4	5	6	7	8	9	10	11	12	New
⬜ 19th Apr 03	37.4	33.8	37.1	33.2	22.6	29.8	30.7	27.8	27.0	27.8	22.9	25.2	
🟩 2nd May 03	38.7	36.4	38.1	34.7	27.5	33.3	32.1	30.9	29.4	29.9	27.2	24.9	
🟨 18th May 03	31.5	24.4	30.8	29.9	21.3	26.4	24.7	28.3	22.4	22.5	16.6	17.4	
🟥 7th Jun 03	29.6	27.6	33.2	15.9	18.3	27.2	22.0	23.0	21.4	22.3	27.2	15.0	70.09

TBN trend

Chart 2 – Ship B – (7th June 03 samples)



	1	2	3	4	5	6	7	8	9	10	11	12	New
⬜ 19th Apr 03	46	88	96	140	480	157	108	142	330	158	149	119	
🟩 2nd May 03	41	43	38	41	100	88	53	65	72	55	57	42	
🟨 18th May 03	58	129	74	83	280	240	360	91	138	91	112	53	
🟥 7th Jun 03	65	87	70	96	117	161	390	400	183	109	66	111	6

Iron Trend

Chart 3 – Ship B – (7th June 03 samples)

CDO analysis results are plotted as trends over a series of the four most recent results. Charts 2 & 3 are examples of two of the comparions made.

The TBN chart shows variations in alkaline reserve between cylinders and allows comparison with the corresponding Iron chart.

In the example shown reserve alkalinity is seen to vary between 15 ~ 33 TBN and Iron 65 ~400 ppm, indicating that there is no obvious relationship between the two charts.

Recommendations were made throughout the study for adjustment of VIT, fuel rack, fuel pressure and temperature to ensure delivery of balanced power between cylinders. Recommendations were also made to check injectors, overhaul cylinder units, etc. The intention was to maintain optimum operating conditions by reducing some of the variables, which might influence or cloud the data being collected.

Engine Performance and Cylinder Drain Oil (CDO) Analysis

Charts 4, 5, 6 & 7 demonstrate a typical procedure for diagnosis of incomplete combustion as the cause of increased wear.

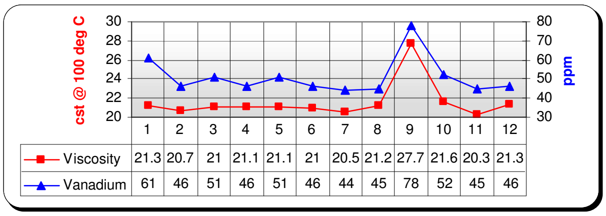
The high Vanadium and high Viscosity of Units 1 & 9 (Chart 4) indicate fuel contamination. And correspondingly high Iron for Units 1 & 9 seen in Chart 5 points to combustion irregularity causing higher wear.

A check of the engine performance report and EDA output may then provide the information to identify the cause of the fuel contamination.

Checking the Fuel Rack (Chart 6) shows that Units 1, 3 & 9 have higher settings. Whilst low MIP in comparison with Vanadium for Units 1 & 9 (Chart 7) infers that combustion is inferior as compared with other cylinders.

Chart 7 demonstrates how changes in the relationship between MIP and Vanadium can indicate even small changes in the efficiency of combustion. This assumes that the relationship between MIP and Vanadium should remain constant if the fuel injected burns completely, and that calorific value available in the fuel is effectively converted to heat energy. The MIP should then correspond with the amount of fuel injected.

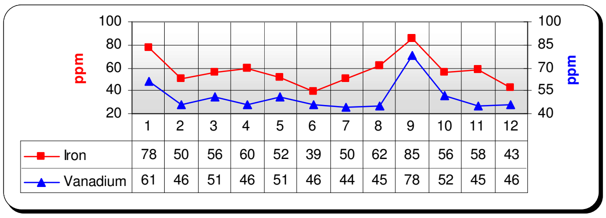
A lower MIP, as compared with other cylinders with similar amount of fuel injected, would indicate, either that the fuel is not completely burned, due to defective atomisation, or the calorific value available in the fuel is not effectively converted to heat energy, due to incorrect timing or blow-by.



	1	2	3	4	5	6	7	8	9	10	11	12
Viscosity	21.3	20.7	21	21.1	21.1	21	20.5	21.2	27.7	21.6	20.3	21.3
Vanadium	61	46	51	46	51	46	44	45	78	52	45	46

High Viscosity and Vanadium for Unit 9 indicate fuel contamination

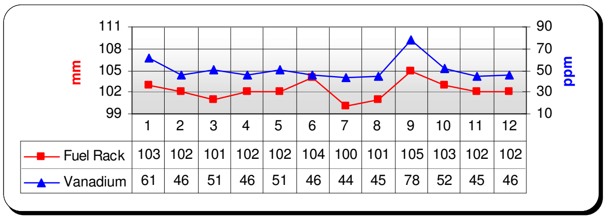
Chart 4 – Ship C (5th June 03 samples)



	1	2	3	4	5	6	7	8	9	10	11	12
Iron	78	50	56	60	52	39	50	62	85	56	58	43
Vanadium	61	46	51	46	51	46	44	45	78	52	45	46

High Vanadium/ high Iron in Units 1 & 9 indicate that a combustion irregularity is causing an increase in wear.

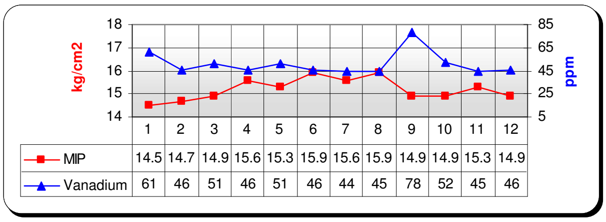
Chart 5 – Ship C (5th June 03 samples)



	1	2	3	4	5	6	7	8	9	10	11	12
Fuel Rack	103	102	101	102	102	104	100	101	105	103	102	102
Vanadium	61	46	51	46	51	46	44	45	78	52	45	46

High Fuel Rack and Vanadium for Units 1 and 9 suggest greater amount of fuel injected

Chart 6 – Ship C (5th June 03 samples)



	1	2	3	4	5	6	7	8	9	10	11	12
MIP	14.5	14.7	14.9	15.6	15.3	15.9	15.6	15.9	14.9	14.9	15.3	14.9
Vanadium	61	46	51	46	51	46	44	45	78	52	45	46

High Vanadium and low MIP in Units 1 and 9 indicate incomplete combustion

Chart 7 – Ship C (5th June 03 samples)

If the fuel does not burn completely, the residue will be scavenged by the cylinder lubricant, thus increasing the Vanadium content in the cylinder drain oil.

Comparison of Fuel Rack, MIP and Vanadium therefore provides an indicator of combustion efficiency.

INVESTIGATIONS INTO INCIDENCE OF LINER WEAR IN THE LARGE BORE 2-STROKE DIESEL ENGINES OF THREE CONTAINER SHIPS

It is proposed that individual cylinder liner wear conditions are being influenced continuously by variations in combustion and lubrication conditions as affected by fuel quality, engine settings, fuel atomisation and ignition. Throughout this project the individual differences between the cylinders were seen to be small and did not have a measurable influence on the overall performance characteristics of the engine in respect of power developed, emissions or fuel oil consumption. However the noted variations appear to influence the conditions in the individual cylinders and offer an explanation for the fluctuations in wear as identified by manual calibration.

Piston Ring & Liner Wear

Calibration of ring groove, ring and liner frequently indicates differing degrees of wear between different cylinder units.

Interpretation of wear conditions using cylinder lubricant drain and engine performance data analysis is able to monitor wear more frequently than is practical by calibration. This method also throws new light on when and why corrosive or other form of wear is taking place and can indicate the steps to be taken to maintain lubricant feed and wear rates at acceptable levels.

It is reported by Schenk, Hengeveld & Aabo [2] that "corrosion is the likely predominant wear mechanism that will determine the wear rate in the next generation of engines, whereas adhesive wear will not be significant" They further state that "high alkalinity 100 BN oils were required to provide adequate wear protection with 3.5% Sulphur heavy fuel" in the conditions they describe. Adjustment of the lubricant feed rate to achieve adequate neutralisation of the acid is likewise understood to be imperative to control acid corrosion to an acceptable level to ensure satisfactory life of rings and liner.

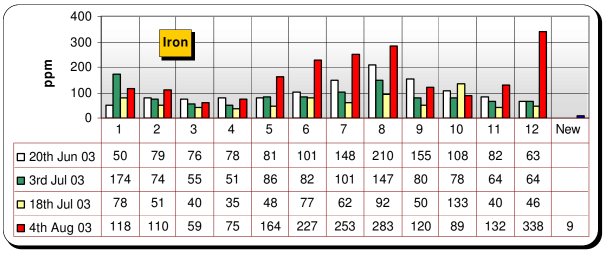
Interpretation of the data from the three MAN.B&W 12K90MC engines has shown that wear, as indicated by the Iron ppm in the drain oil, increases when a high sulphur is in use, and decreases with low sulphur fuel. No evidence was seen to indicate that acid condensation caused unusual wear, even when high sulphur fuel coincided with low lubricant feed. On the other hand frequent instances were observed of larger fluctuations in wear resulting from variations in combustion conditions.

Evaluation of Wear

In order to evaluate the degree of wear, as indicated by the Iron content in the CDO, the authors use empirical terms for the purposes of their comparisons. Iron readings up to 150 ppm are considered as "normal wear", 150 ppm to 400 ppm as "high wear", and when Iron exceeds the figure of 400 ppm as "unusual wear".

Abrasive wear mechanisms are discussed by Demmerle, Barrow, Jacquet and Terretaz [3] and described variously as adhesive, micro-seizure, scuffing, and sudden severe wear. In this paper the authors do not define the mechanism and consider the iron readings from CDO analysis only as an indicator of the total wear from interaction between cylinder liner, piston rings and piston ring grooves. It is assumed that the greater part of the iron in the cylinder drain oil is coming from wear between the rings and cylinder liner. The assessment of ring groove wear using CDO analysis is reported by Kim, Hwang, Fogh & Jakobsen report [1].

Although Iron in CDO data is being collected continuously and compared to that of liner wear calibrations the only inference drawn is that of variable wear mechanisms. Consequently no attempt is made by the authors to relate the two sets of data (CDO analysis and calibrated wear). The fluctuating and sporadic nature of wear of pistons rings and liners, combined with variations by associated fuel and system oil dilution, are likely to preclude even an empirical dependency. (Chart 8)



	1	2	3	4	5	6	7	8	9	10	11	12	New
□ 20th Jun 03	50	79	76	78	81	101	148	210	155	108	82	63	
🟩 3rd Jul 03	174	74	55	51	86	82	101	147	80	78	64	64	
🟨 18th Jul 03	78	51	40	35	48	77	62	92	50	133	40	46	
🟥 4th Aug 03	118	110	59	75	164	227	253	283	120	89	132	338	9

Fluctuation of Iron ppm between individual cylinders indicating wide variations in wear.

Chart 8 – Ship B (4th August 03 samples)

Corrosive wear

Before the introduction of residual fuels in marine diesel engines in the early 1950's corrosive wear was not considered a concern. The use of residual fuels introduced sulphur as a component of the fuel and prompted the development of alkaline cylinder lubricants which could neutralize the acid formed by the combustion of sulphur.

The development of alkaline cylinder lubricants over the past 50 years, and improvements to the design of the engine [2], mean that corrosive wear in the diesel cylinder liner of a modern design engine may fluctuate within a narrower range than expected when the sulphur content in the fuel increases from say 1% to 4%. The current study indicates that "unusual wear" due to acid corrosion is now a rare occurrence.

It is generally understood that the amount of acid condensation on the cylinder liner wall is influenced by the following:

1. *Sulphur content of the fuel*

   The amount of sulphur trioxide which is formed in the combustion gases, and hence the amount of "sulphur acids" which condense on the liner wall, increases in proportion to the amount of sulphur present in the fuel.

2. *High pressures in the combustion zone*

   The dew-point of sulphuric acid may be as high as 280^0C in a modern high Pmax engine burning a 3.5% Sulphur fuel [2], leading to a greater amount of acid condensation compared to an older design low Pmax engine at the same fuel consumption.

3. *Liner wall temperature*

   The increase in dew-point would normally mean that modern design engines should need to operate with higher liner wall temperatures to reduce the incidence of acid condensation, and also require that cylinder lubricants maintain a satisfactory lubricant film at the higher liner wall skin temperatures. It is noted however that cylinder liner wall temperatures have not increased over the last 10-15 years in MAN B&W MC series engines indicating that design changes have been able to address the tendency for increased acid condensation at higher cylinder pressures. It is reported by Mikkelsen, Rolsted & Jakobsen [4] that cylinder liner temperatures have decreased in the top of the cylinder liner running surface for those engines with the so-called high top land piston.

Cylinder Lubricant Feed Rates & CDO Analysis

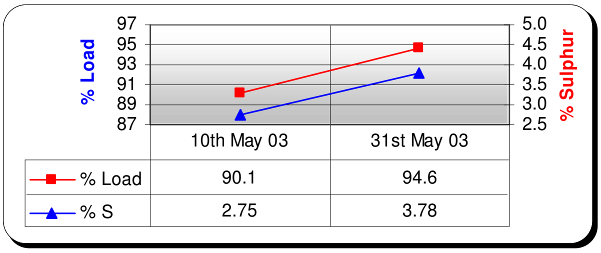
Over recent years cylinder lubricant feed has been reduced from previous "normal" level of 1.6 g/kWh (1.2 g/ bhph) to current engine manufacturer recommendations in the range 0.7-1.34 g/kWh (0.5-1.0 g/bhph)

In the year 2000 Flame Marine introduced a service to monitor lubrication conditions as ship operators began to apply the new feed recommendations from the engine manufacturers. Similar services are now offered by major lubricant suppliers to ensure that lubricant feed rates are not reduced to a point at which engines are inadequately lubricated.

In order to monitor wear conditions in an engine, with minimum delay between sampling and diagnosing a situation of high wear, on-board test kits [5] are also available to provide rapid response to abnormal wear enabling the operator to take immediate corrective action to boost lubricant feed.

In such circumstances a recommendation may be made to increase the lubricant feed in order to maintain an adequate alkaline reserve of the drain oil to overcome the perceived corrosive wear.

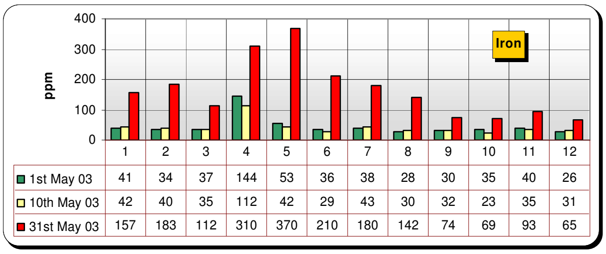
The authors have not observed any situation that requires cylinder lubricant feed rate to be increased above the range recommended by the engine manufacturers. Many instances have however been noted of CDO Iron ppm increasing, and alkaline reserve reducing, as a consequence of increased acid condensation. Nevertheless indications are that the reserve remains adequate to prevent corrosive wear, and that the increased Iron does not indicate higher than normal wear.



	10th May 03	31st May 03
■ % Load	90.1	94.6
▲ % S	2.75	3.78

Fuel Sulphur & Engine Load are higher for 31st May 03 than Sulphur and Load on 10th May 03.

Chart 9 – Ship A (31st May 03 samples)



	1	2	3	4	5	6	7	8	9	10	11	12
🟩 1st May 03	41	34	37	144	53	36	38	28	30	35	40	26
🟨 10th May 03	42	40	35	112	42	29	43	30	32	23	35	31
🟥 31st May 03	157	183	112	310	370	210	180	142	74	69	93	65

Variation in Iron between Units indicates that factors other than Sulphur are influencing wear.

Chart 10 – Ship A (31st May 03 samples)

An example of the effect of a higher sulphur fuel is demonstrated in Charts 9 to 13. Samples were taken on the 10th May when the Sulphur content of the fuel in use was 2.75%. the next set of samples were drawn on the 31st May when a higher Sulphur fuel of 3.78% was in use.

Chart 10 shows Iron ppm of the drain oil whilst using the two different fuels indicated in Table 2.

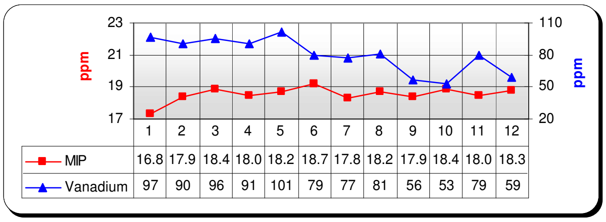
Date Bunkered	Port Bunkered	Sulphur Content	Dates in Use
20th April 03	Rotterdam	2.75 %	1st May 03 10th May 03
12th May 03	Singapore	3.78%	31st May 03

Table 2- Bunker details

Iron ppm is higher on the 31st May due to the higher Sulphur. However the large fluctuations in Iron ppm between individual units point to factors other than Sulphur causing the higher Iron in Units 1 to 8 & 11. Units 9, 10 & 12, being unaffected by "other factors", demonstrate a small increase of about 40 ppm Iron as being caused by the higher Sulphur.

The factors influencing the higher Iron in Units 1 to 8 & 11 are explored in Charts 11, 12 & 13.

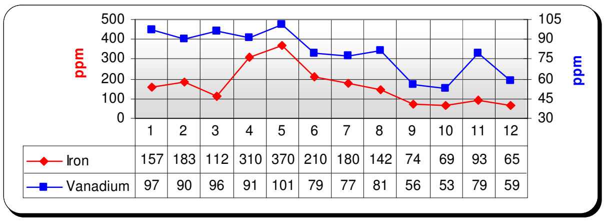
In Chart 11 the high Vanadium relative to the MIP for Units 1 – 8 & 11 infers incomplete combustion of a small part of the fuel injected, whereas in Units 9, 10 & 12 Vanadium is low in comparison with MIP.



Vanadium and MIP Comparison

Chart 11 – Ship A (31st May 03 samples)

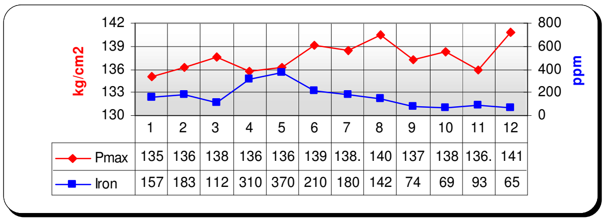
Chart 12 shows that higher Iron in Units 1 to 8 & 11 corresponds with higher Vanadium, which again indicates that incomplete combustion is influencing the Iron ppm. On the other hand Units 9, 10 and 12 have low Iron compared to Vanadium ppm.



Iron and Vanadium Comparison

Chart 12 – Ship A (31st May 03 samples)

In Chart 13 a further, though weak, indicator is provided by Units 4 & 5 where the highest Iron values correspond with lower Pmax.



Pmax and Iron Comparison

Chart 13 – Ship A (31st May 03 samples)

The implication therefore is that the increase in Iron ppm for Units 1 to 8 & 11 is influenced more by variation in combustion conditions and disruption of the lubricant film by fuel, rather than the increase in Sulphur content in the fuel.

Flame Marine previous experience, and consequent advice, had been that "good practice" required reserve alkalinity of the cylinder drain oil to be maintained in the range 20 ~ 30 TBN to provide adequate protection against corrosive wear, in order to ensure that Iron, as the indicator of wear, is maintained below 150 ppm.

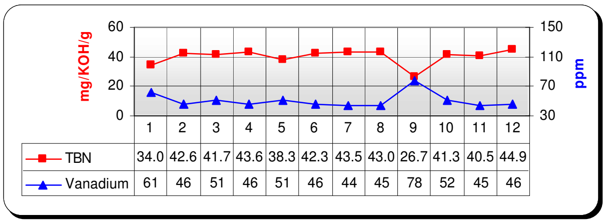
Knowledge acquired over the period 2002 and 2003, as well as the introduction and application of new methods of cylinder lubrication suggests that the previous "good practice" advice to maintain reserve alkalinity of the drain oil in the range of 20 ~ 30 TBN is not necessarily valid.

The evidence observed in the study during 2003 of over 4,000 CDO analyses, from both older engines with 70,000 operating hours and new-buildings, contradicts the "good practice" advice. The indication is that corrosive wear is low even when the alkaline reserve is less than 10 TBN, and that factors other than corrosion are having a greater influence on wear in normal operating conditions.

It is generally accepted when the CDO analysis shows high Iron ppm values coinciding with low alkalinity that corrosive wear is taking place. When this condition is manifested in only one or two cylinders it is unlikely to be the correct conclusion.

The more likely reason for the lower TBN reading of CDO from the affected cylinders is dilution by fuel contamination, and that the increase in Iron is a consequence of disruption of the lubricant film by fluctuations in the atomisation and spray pattern of the fuel injected.

Chart 14 shows the effect of minor fuel contamination on TBN in Unit 1 and a greater amount of fuel contamination in Unit 9.



	1	2	3	4	5	6	7	8	9	10	11	12
TBN	34.0	42.6	41.7	43.6	38.3	42.3	43.5	43.0	26.7	41.3	40.5	44.9
Vanadium	61	46	51	46	51	46	44	45	78	52	45	46

Contamination by fuel of the drain oil from Units 1 and 9 is diluting the TBN.

Chart 14 – Ship C (5th June 03 samples)

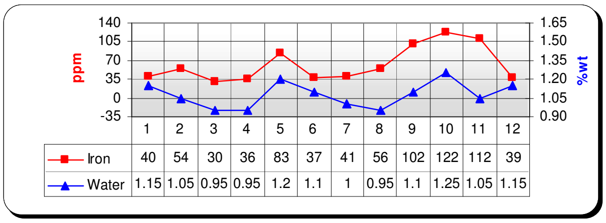
Abrasive Wear

Data from the engines subject of this study indicate that even small variations in combustion conditions, and not corrosive wear, is the most prevalent cause of higher wear in the 2-stroke marine diesel engine cylinder.

Other causes of unusual abrasive wear are:

- disruption of the cylinder lubricant film by Water
- presence of Cat-fines in the injected fuel.

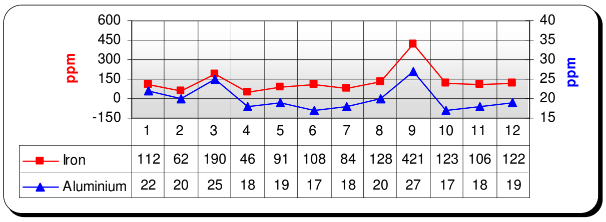
The occurrence of wear due to Water and Cat-fines is observed to be less frequent, as a result of precautions being taken to reduce ingress of Water into the cylinder, and care being taken to remove Cat-fines by centrifugal purification and filtration of the fuel. Neglect of Water contamination (Chart 15), and inadequate care taken to ensure removal of Cat-fines from the fuel appears to correlate with the incidence of high wear attributable to these factors (Chart 16).



	1	2	3	4	5	6	7	8	9	10	11	12
Iron	40	54	30	36	83	37	41	56	102	122	112	39
Water	1.15	1.05	0.95	0.95	1.2	1.1	1	0.95	1.1	1.25	1.05	1.15

Water is influencing Iron ppm particularly in Units 5 and 10.

Chart 15– Ship C (8th September 03 samples)



	1	2	3	4	5	6	7	8	9	10	11	12
Iron	112	62	190	46	91	108	84	128	421	123	106	122
Aluminium	22	20	25	18	19	17	18	20	27	17	18	19

Cat-fines influencing Iron ppm particularly in Units 3 and 9.

Chart 16 – Ship B (24th October 03 samples)

Abrasive Wear due to combustion conditions

Study of CDO analyses demonstrates that that high Iron frequently coincides with low alkaline reserve in the drain oil.

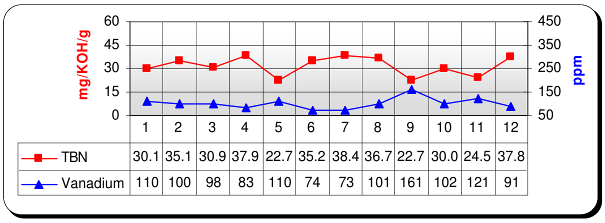
The logical conclusion is that acid condensation is causing the low reserve. To arrive at this conclusion requires the assumption that the increase in Iron is a consequence of increased acid condensation, which poses the questions:

Why is more acid being formed in this cylinder than in other cylinders?

If more acid is being formed then this can be due to more fuel being injected, higher cylinder pressure or lower liner wall temperature.

What other influences will cause the TBN to be lower than other cylinders?

Dilution of the CDO by fuel contamination, or system oil leakage into the under-piston space, would give rise to a lower TBN value. Chart 17 shows that Fuel contamination is diluting the CDO in several cylinders of which Units 5, 9 and 11 are the most affected.

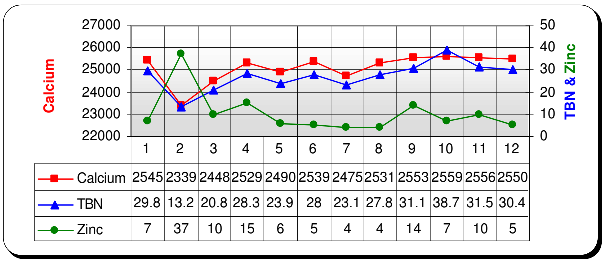


	1	2	3	4	5	6	7	8	9	10	11	12
TBN	30.1	35.1	30.9	37.9	22.7	35.2	38.4	36.7	22.7	30.0	24.5	37.8
Vanadium	110	100	98	83	110	74	73	101	161	102	121	91

Fuel contamination diluting the TBN in Unit 9

Chart 17 – Ship C (18th October 03 samples)

Chart 18 demonstrates System oil (as indicated by Zinc) contaminating the cylinder drain oil from Unit 2 and diluting both TBN and Calcium. (Note that Calcium value of the fresh oil is 25,600 ppm)



	1	2	3	4	5	6	7	8	9	10	11	12
Calcium	2545	2339	2448	2529	2490	2539	2475	2531	2553	2559	2556	2550
TBN	29.8	13.2	20.8	28.3	23.9	28	23.1	27.8	31.1	38.7	31.5	30.4
Zinc	7	37	10	15	6	5	4	4	14	7	10	5

System oil contamination diluting the TBN and Calcium in Unit 2

Chart 18 – Ship A (2nd October 03 samples)

Conditions of combustion are influenced by the following:

- differences in the timing of fuel injection (which can vary between cylinders)
- incorrect fuel temperature and pressure (affecting all cylinders)
- poor atomisation by a faulty injector (affecting individual cylinders)
- poor atomisation due to presence of asphaltenes in the fuel (affecting all cylinders)
- combustion characteristics of the fuel (affecting all cylinders).

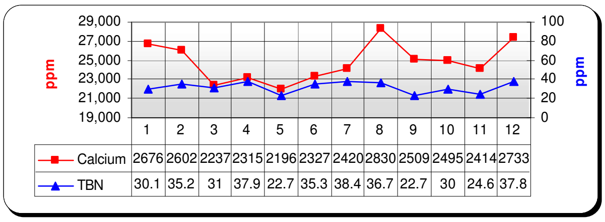
Any one, or combination, of the above can cause disruption of the lubricant film as a result of fuel contaminating the lubricating oil, local thermal over-loading of the liner wall and late completion of combustion of the fuel charge.

It is proposed that uneven burning of the fuel resulting from an irregular spray pattern from the injector is the most frequent reason for an increase in the Iron ppm in the drain oil. It is observed that the aberration in the spray pattern of the fuel can be temporary and may correct itself. This can happen due to changes in the consistency of the fuel, as a result of the presence of asphaltenes; these are known to cause variations in viscosity and temporarily reduce the flow of fuel through the injector nozzle holes. In other cases one or more holes in the injector tip may become obstructed or blocked requiring replacement of the injector. Recognised factors that influence the spray pattern include temperature, consistency (presence of asphaltenes) and pressure of the fuel.

Incompletely burned fuel is scavenged by the cylinder lubricant and detected in the CDO by presence of Vanadium and increase in Viscosity, as well as by other indicators. As fuel is injected at the rate of 165 g/kWh into the cylinder and cylinder lubricant at 1.35 g/kWh, it means that a quantity of unburned fuel as low of 0.1% of that injected and remaining in the cylinder will result in a dilution of 12% of the cylinder lubricant. Dilution of the cylinder lubricant film by fuel impingement from a faulty injector can also be expected to reduce the lubrication properties of the cylinder lubricant and cause an increase in abrasive wear.

An irregular injector spray pattern may also cause late ignition, uneven burning and late completion, burning away the oil film from the liner surface [2]. A fuel with poor ignition or poor combustion characteristics will also cause late burning. The burning of cylinder lubricant is detected in the CDO by the presence of high Calcium ash.

Chart 19 shows that cylinder lubricant is being burned in Units 1, 2,& 8 to 12 as indicated by the high Calcium relative to TBN.



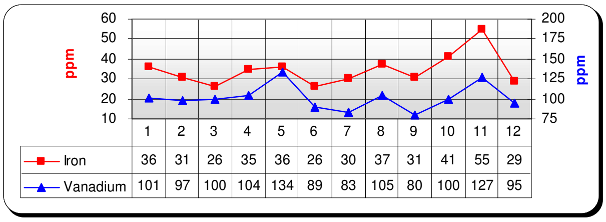
	1	2	3	4	5	6	7	8	9	10	11	12
■ Calcium	2676	2602	2237	2315	2196	2327	2420	2830	2509	2495	2414	2733
▲ TBN	30.1	35.2	31	37.9	22.7	35.3	38.4	36.7	22.7	30	24.6	37.8

High Calcium relative to TBN in Units 1, 2 & 8 to 12 indicates burning of cylinder lubricant

Chart 19 – Ship C (18th October 03 samples)

It should be noted that high Calcium ash also occurs in normal combustion conditions when cylinder lubricant feed is excessive.

Incomplete combustion, of what may be only a small part of the fuel charge, is observed to affect the lubrication characteristics of the cylinder lubricant film and cause an increase in the Iron ppm in the CDO. The Iron content in the CDO analyses from a well maintained and operated engine, with lubricant feed as low as 1 g/kWh, may be in the range of 30 ~ 40 ppm, as shown in Chart 20. A very minor change in combustion conditions in Unit 11 is seen to cause the Iron to increase by as little as 15 ppm or a larger deterioration in combustion cause an increase in Iron of 300ppm as was seen in Chart 12.



	1	2	3	4	5	6	7	8	9	10	11	12
■ Iron	36	31	26	35	36	26	30	37	31	41	55	29
▲ Vanadium	101	97	100	104	134	89	83	105	80	100	127	95

Minor changes in combustion conditions influencing wear

Chart 20 – Ship C (13th November 03 samples)

It may be reasonable to assume that incomplete combustion produces less acid, since dew point of acid is a function of the amount of sulphur in the fuel, the gas pressure and the temperature of the surface on which it may condense [2]; consequently incomplete combustion is unlikely to influence dew point such that acid condensation and corrosive wear would increase.

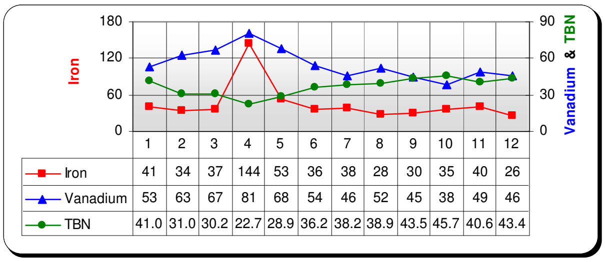
In conditions of an irregular injector spray pattern evidence is seen of fuel contaminating the drain oil. It is therefore proposed by the authors that the fuel, which is diluting the cylinder oil, in a unit affected by incomplete combustion, is likewise diluting the alkaline reserve. This dilution results in a lower TBN reading than the TBN observed in the CDO of cylinders which have good combustion conditions, and which, logically, are producing more acid.

It is the observation of the authors that low TBN and high Iron in the CDO of an affected cylinder is likely to be a consequence of a variation in combustion conditions and is not a reason to increase the lubricant feed rate to that cylinder.

It should however be noted that another cause of low alkalinity in the drain oil is due to dilution by system oil from the crankcase – see Chart 18. System oil is transported by the piston rod through the stuffing box gland in the piston rod diaphragm into the under-piston space. This leakage has no detrimental effect on the cylinder lubrication, but will dilute the CDO and disguise and dilute the CDO analysis results. The effect will be to cause the readings for TBN, Iron, Vanadium, Calcium, Viscosity etc. to be lower.

Simultaneous contamination by Fuel and System oil may mask the conditions in an affected cylinder whereby Iron and Viscosity would have similar readings to other cylinders and appear normal.

It is observed therefore that a low TBN reading in one or two cylinders of an engine is unlikely to be due to an increase in acid condensation and in most cases is not an indication of corrosive wear, even when the associated Iron reading is high.



	1	2	3	4	5	6	7	8	9	10	11	12
Iron	41	34	37	144	53	36	38	28	30	35	40	26
Vanadium	53	63	67	81	68	54	46	52	45	38	49	46
TBN	41.0	31.0	30.2	22.7	28.9	36.2	38.2	38.9	43.5	45.7	40.6	43.4

Unstable combustion in Unit 4 is causing increase in Iron ppm.
Resultant Fuel contamination is diluting TBN.

Chart 21 – Ship A (1st May 03 samples)

Chart 21 provides an example of low TBN coinciding with high Iron. Alkalinity of Unit 4 is low at 22.7 TBN and Iron is high at 144 ppm, which might indicate corrosive wear. However the coincidence of high Vanadium and high Iron suggests inferior combustion, fuel dilution and, hence abrasive wear as the cause of the high Iron.

Abrasive wear due to Blow-by

Incomplete and late combustion can lead to:

- a residue of calcium ash and carbon from the burning of the cylinder lubricant, and
- a residue of carbon from incomplete combustion of the fuel, and ash from impurities in the fuel,

The residues may form deposits on the top land of the piston, in the ring grooves and on the ring lands. One property of the lubricant is to scavenge this debris and carry it away to the drain. The efficiency of scavenging is a function of the available mass of lubricant, the dispersant reserve of the lubricant, and the mass of debris to be scavenged.

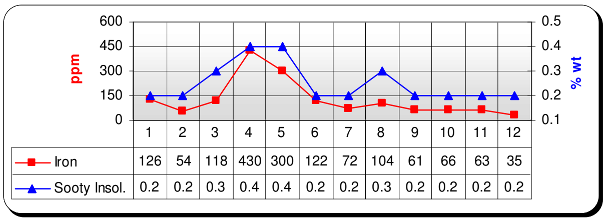
A high lubricant feed rate will ensure adequate dispersant reserve, but at the risk of excess lubricant being burned and the consequent lubricant ash contributing to the debris to be scavenged.

Minor blow-by past 1st ring of Unit 4

Pic 1 – Ship A (Inspection on 17th March 03)

Minor blow-by past 1st ring of Unit 5

Pic 2 – Ship A (Inspection on 17th March 03)



	1	2	3	4	5	6	7	8	9	10	11	12
Iron	126	54	118	430	300	122	72	104	61	66	63	35
Sooty Insol.	0.2	0.2	0.3	0.4	0.4	0.2	0.2	0.3	0.2	0.2	0.2	0.2

Minor blow-by on Units 4 and 5

Chart 22 – Ship A (6th March 03 samples)

As lubricant feed rates are reduced a threshold is reached when the quantity of cylinder lubricant is inadequate to scavenge the Carbon and the Calcium ash. Both over-lubrication and under-lubrication can therefore result in a build up of deposits in the ring grooves and on the piston top land.

When debris from the fuel and burned lubricant is not successfully scavenged by the cylinder lubricant, it will accumulate in the piston ring groove and restrict the free movement of the piston ring, leading to ring seizure and blow-by (Pic 1 & 2). Even partial ring seizure will allow blow-by of the combustion gases to disrupt the cylinder lubricant film and cause abrasive wear of a narrow band of the liner circumference. An associated increase in temperature of ring and liner will produce distortion of the ring and incremental development of blow-by.

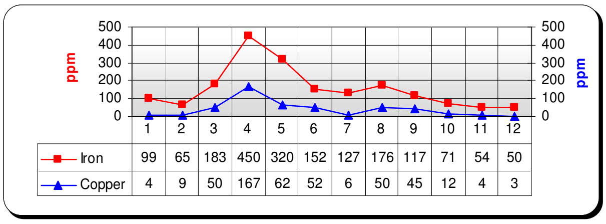
Blow-by as detected by CDO analysis is shown in Chart 22, where high Iron corresponds with high Insolubles. Other factors considered when investigating signs of blow-by are Vanadium content and Viscosity of the CDO, as well as other analysis parameters. Temperature readings from liner wall sensors, when fitted, are also taken into account.

Abrasive wear due to Piston crown/ piston skirt abrasion

Following the overhaul of a piston and cylinder unit, high Iron readings may be expected as the unit beds in. However CDO analyses show that wear is not always high during running-in even when lubricant feed rate is not increased.

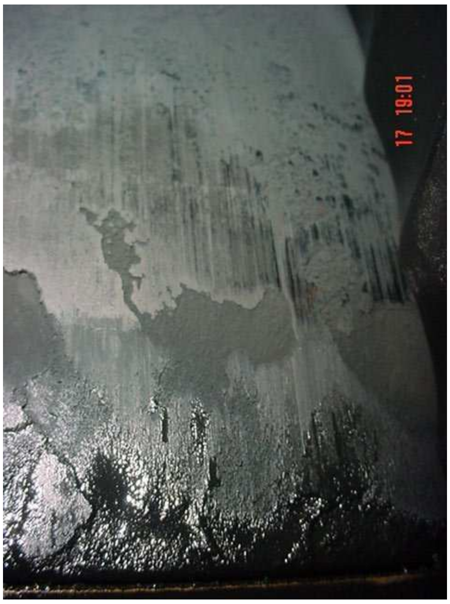
When wear does occur the high Iron in the CDO frequently corresponds with high Copper. This indicates abrasion between the piston skirt and liner wall as the piston beds in, and as the brass rubbing strip wears down. Chart 23 shows high Iron and Copper readings in Unit 4 at 151 hours following overhaul.

However piston skirt abrasion against the liner wall is also seen to occur whenever there is a build up of deposit on the piston topland. Abrasive wear between piston and liner wall is reported [2][6] to be due to deposits on the piston topland which disturbs the lubricant film and may cause scuffing.



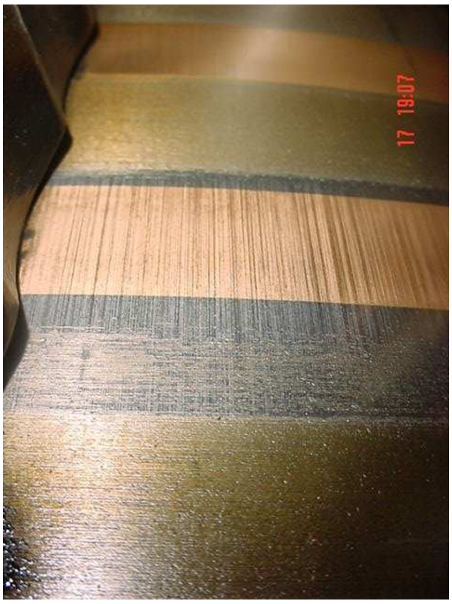
Unit 4 has high Iron and Copper during running-in.

Chart 23 – Ship A (7th February 03 samples)



Deposits on Unit 4 piston top land abrading the liner wall.

Pic 3 – Ship A (Inspection on 17th March 03)



Initial wearing in of copper band on the piston skirt of Unit 4.

Pic 4 – Ship A (Inspection on 17th March 03)

The authors of this current paper would add that the occurrence of deposit on the top land (Pic 3) tends to be linked also with abrasion between the piston skirt and the liner wall. The deposit build up on the piston topland appears to be restricting free movement of the piston, possibly affecting the normal alignment of the piston. In these circumstances there is a scraping action of the piston skirt (Pic 4) against the liner wall disrupting the lubricant film and causing abrasive wear. In the period during 2002 and 2003 the authors have noted frequent occurences in both MAN B&W and Sulzer engine designs.

Coincidentally it is noted in many cases that system oil dilution of the CDO increases when piston skirt abrasion is occuring, indicating that disturbance to the piston by the deposit build up also affects alignment of the piston rod.

It is observed that engines fitted with a "piston cleaning ring" (PC ring) or "anti-polishing ring" (APR) set into the liner wall can remove deposit and limit the build up on the piston top land. Inspections and drain analyses indicate the PC or APR rings appear to improve cleanliness of the top land but are unable to maintain complete cleanliness as demonstrated by the three engines subject of this study which have PC rings.

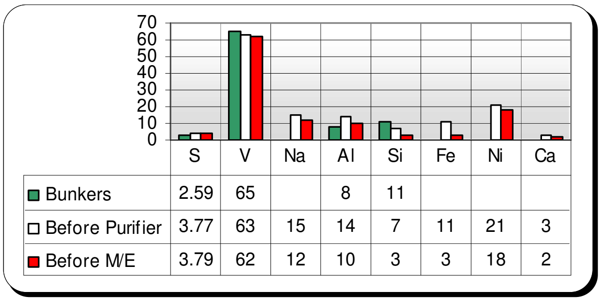
Abrasive Wear by Cat-fines

ISO fuel specifications limit Cat-fines to 80 ppm in the fuel as delivered, above which the fuel is out of specification and unacceptable for use. The limit of 80 ppm presupposes that the fuel will be subjected to settling, centrifugal separation and filtration to reduce the Cat-fines content of the fuel to a level which should not cause wear. For the purpose of this study the authors consider only the Aluminium component of the Catalytic fines and not the Silicon.

(Cat-fines are composed of Aluminium and Silicon. However Silicon is also a component of the cylinder lubricant additive package. Silicon is therefore always present in the cylinder drain oil even when there are no Cat-fines in the fuel. When Cat-fine content of the fuel is low it is therefore difficult to establish any clear relationship between Silicon content of the fuel and Iron content in the CDO.)

When there are Cat-fines present in the fuel, Aluminium is found in the cylinder drain oil as a result of fuel ash and fuel contamination being scavenged by the cylinder lubricant. It is observed that the amount of Aluminium in the CDO from each cylinder normally relates to the Aluminium content of the fuel as injected. In such circumstances the Cat-fines do not appear to be influencing wear.

However when the Aluminium content of drain oil from one or more cylinders exceeds that of other cylinders, or greatly exceeds that of the fuel, a related increase in Iron ppm may be seen. Evidence indicates that presence of amounts of Aluminium in the fuel as injected may cause abrasive wear of the ring grooves [1] and influence cylinder liner wear. When care is taken to ensure efficient centrifugal separation and filtration of the Cat-fines the risk of them entering the engine is reduced.

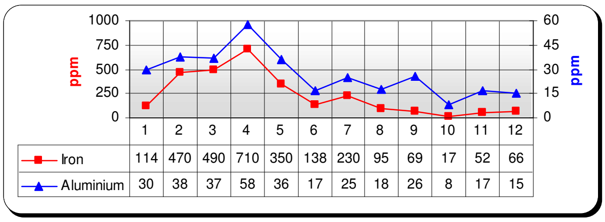


	S	V	Na	Al	Si	Fe	Ni	Ca
🟩 Bunkers	2.59	65		8	11			
☐ Before Purifier	3.77	63	15	14	7	11	21	3
🟥 Before M/E	3.79	62	12	10	3	3	18	2

Fuel Analysis Comparison

Chart 24 – Ship A (18th February 03 samples)

However, even Cat-fine content of 10 ppm Al "before ME Pump" as seen in the Fuel analysis in Chart 24, can cause abrasive wear. Chart 25 shows a close relationship between Iron and Aluminium when using the above Fuel, suggesting that Cat-fines are influencing wear in Units 1 to 7.



	1	2	3	4	5	6	7	8	9	10	11	12
Iron	114	470	490	710	350	138	230	95	69	17	52	66
Aluminium	30	38	37	58	36	17	25	18	26	8	17	15

Cat-fines are influencing Iron ppm in Units 1 to 7.

Chart 25 – Ship A (18th February 03)

Influence of Water on abrasive wear

Water enters the engine with the scavenge air and the amount of Water taken into the combustion chamber is a function of:

- Ambient humidity and temperature.
- Efficiency of operation of Air coolers and Water separators
- Engine load and consequent air requirement

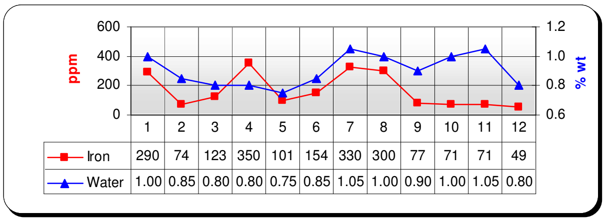
Water leakage from Air-coolers, and inefficient operation of the Water separator and Water drain arrangements, can allow a greater amount of Water to be entrained with the scavenge air and be transported into the combustion chamber.

It is reported that the presence of Water can replace the oil film on the liner [2] and give rise to abrasive wear.

A crack in the liner, or, in some engine designs, a leaking liner O-ring can also be a source of Water in the cylinder.

In the study of other engines outside the scope of this paper it has been observed that high Iron ppm coincides with both high Water and high Viscosity. It is understood that when emulsification of cylinder lubricant film takes place there is deterioration in the lubrication characteristics. In one documented case severe abrasive wear was indicated by Iron content of the CDO exceeding 5,000 ppm in conjunction with Water of 1.45% and Viscosity 36 cst.

Although Water content of the CDO exceeded 1% on many occasions for the three engines subject of this paper, there were few instances of Water causing emulsification. There were no instances when high Water disrupted the lubricant film and caused severe abrasive wear.



	1	2	3	4	5	6	7	8	9	10	11	12
Iron	290	74	123	350	101	154	330	300	77	71	71	49
Water	1.00	0.85	0.80	0.80	0.75	0.85	1.05	1.00	0.90	1.00	1.05	0.80

Water Influencing Iron in Units 1, 7 and 8

Chart 26 – Ship A (16th March 03 samples)

Chart 26 shows high Water influencing Iron in Units 1, 7 and 8. Similar high Water of 1.00 – 1.05% is not affecting Units 10 and 11. (The high Iron in Unit 4 is unrelated to Water, which is running-in following overhaul – see Chart 23.)

In most cases it is likely that the abrasion resulting from emulsification and disruption of the lubricant film by the small amount of Water found in the cylinder drain oil, is occurring in a strictly localized area, such as is the case for micro-seizure of piston rings. However a cracked liner or badly leaking liner O-ring can result in catastrophic wear attributable to total breakdown of the lubricant film. In such cases Viscosity and Iron readings of the drain oil are very high.

CONCLUSIONS

The cylinder drain oil (CDO) samples have been measured by spectrographic analysis during the course of the trial on the three MAN.B&W 12K90MC engines. Understanding the limitations of this method for measurement of liner and ring wear, as reported by Saddler [5], it is observed that the main factors influencing Iron ppm, and hence wear, in normal conditions of operation are:

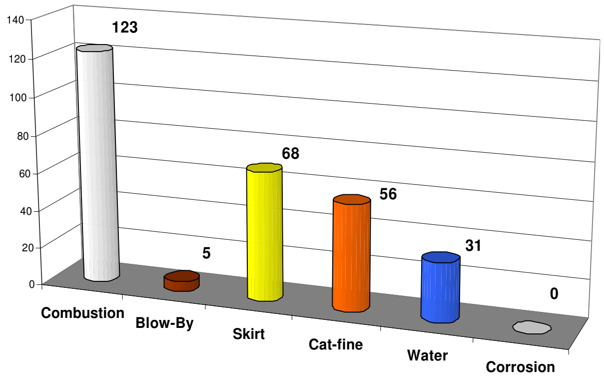
- Amount of Sulphur entering the engine with the fuel
- Quality of atomisation and combustion characteristics of the fuel
- Deposits restricting free movement of the piston
- Blow-by of combustion gases past the ring pack of the piston
- Presence of cat-fines in the fuel
- Water ingress into the combustion chamber.

In given conditions, operation of an engine with high sulphur fuels is seen to cause a greater amount of acid condensation on the liner wall than low sulphur fuels. However the authors have not seen any instances of high corrosive wear in any of the three engines burning fuel with Sulphur content ranging between 2.56% – 4.00%

Greater control over corrosive wear of cylinder liners of modern design engines is being achieved by new developments in the design of pistons and cylinder liners. There are also improvements in the methods of lubrication offered by new designs of lubricators [7] which take into account load of the engine and sulphur content in the fuel. And there are improved cylinder lubricant formulations from the major lubricant companies. The combined effect is that corrosive wear is seen to be controlled, seldom giving rise to excessive wear rates in modern engines. For the three 12K90MC engines studied in this paper it is noted that cylinder liner wear calibrations indicate wear ranging 0.04-0.08 mm/1000hours between the cylinders with the highest and lowest wear. At the low cylinder lubricant feed rate, 0.8 – 1.0 g/kWh, employed this represents a good low and narrow variation of wear.

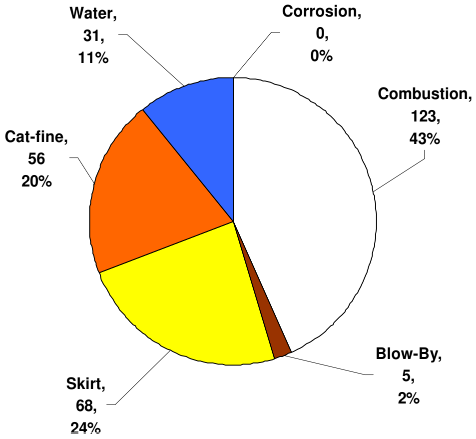
Incidence of wear

From a total of 672 CDO samples there were 283 samples showing increased wear.



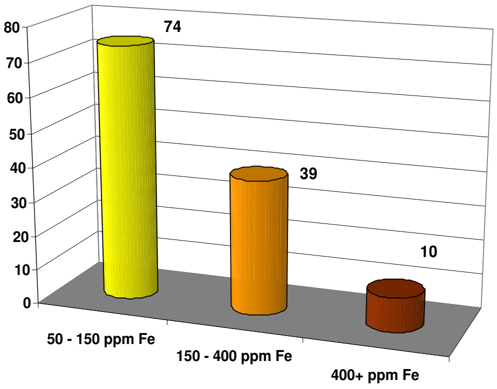
Number of Incidences.

Chart 27 – Incidences of wear by type of wear and by cylinder on all 3 ships from total 672 drain oil samples



Percentage of Incidences.

Chart 28 – Incidence of types of wear as percentage of the 283 samples which showed increased wear



Number of Incidences of Combustion related wear, broken down into "normal", "high" and "unusual".

Chart 29 – Breakdown by degree of combustion related wear by cylinder for all 3 ships

Chart 27 shows the number of instances of wear due to combustion conditions amounting to 123, piston skirt abrasion 68, Cat-fines 56, Water 31, and Blow-by 6. Corrosive wear due to acid condensation was always evident, but not seen to be causing high wear even when using high sulphur fuel, low cylinder lubricant feed and at high engine load.

Chart 28 shows the different types of wear as a percentage of the 283 samples.

Chart 29 breaks down the incidences of combustion related wear according to severity, thus "normal wear" up to 150 ppm, "high wear" from 150 ppm to 400 ppm and in excess of 400 ppm as "unusual wear".

Incidence of wear due to combustion conditions:

Variations in the quality of combustion is seen to cause wide and frequent fluctuations in wear, albeit temporary, as a result of anything from an obstruction in one jet of an injector, to loss of the injector tip. Variations in the consistency of the fuel due to presence of asphaltenes are also influencing the atomisation characteristics, as do fluctuations in the injection temperature and combustion characteristics of the fuel.

Variations in conditions of fuel combustion are seen to be the predominant cause of fluctuations in Iron ppm in the engines subject of this study.

Incidence of wear due to piston skirt abrasion:

Abrasion between piston skirt and liner wall is observed frequently in most of the engines that were studied.The drain analyses are able to identify abrasion between piston skirt and liner. But the they are not able to differentiate skirt abrasion from simultaneous wear that is reported [2] [6] to occur between the piston crown and liner wall.

Incidence of wear due to blow-by:

Over the period of the study of the three engines there were some instances of minor blow-by, but no instance of unusual blow-by due to partial ring seizure or ovality at top of stroke. During normal engine operating conditions there is always an insignificant amount of blow-by of combustion gases past the ring pack. However significant blow-by due to ring seizure, as opposed to blow-by due to liner ovality, was seen only infrequently in 200 other engines studied by Flame Marine over the period of 2002 and 2003. Instances identified as "minor blow-by" occurred more frequently.

Incidence of wear due to Cat-fines:

The low frequency of wear due to presence of Cat-fines appears to reflect the care given by engine room staff to ensure satisfactory centrifugal separation and filtration. Presence of total Cat-fines in the fuel as bunkered in the order of 40 ppm is seen to have little or no influence on wear if the fuel treatment plant is correctly operated. Whereas fuel with less than 20 ppm total Cat-fines is seen to cause abnormal wear when inadequate care is taken to ensure correct separation and filtration. Frequency of abrasion by Cat-fines therefore appears to be related more to correct fuel treatment than to prevalence and amount of Cat-fines in the fuel.

Incidence of wear due to water:

Water in the combustion chamber was an infrequent and insignificant cause of unusual wear in the three engines, and similarly infrequent in the 200 other engines monitored by Flame Marine Ltd during 2002 and 2003. Drain sample analyses indicated that there were few cases when presence of Water caused emulsification of the drain oil and increase in viscosity. Equally infrequent were examples when high Iron in the cylinder drain oil was attributable to high water content. Disruption by Water of the lubricant film and micro-seizure of the rings can be allayed by ensuring efficient operation of the Air-coolers and Water separators, and maintenance of drains free of obstruction.

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