CB(1)736/12-13(05)

For discussion on
25 March 2013

LEGISLATIVE COUNCIL
PANEL ON ENVIRONMENTAL AFFAIRS

Upgrading the Diesel Standard for Local Vessels

PURPOSE

This paper seeks Members' views on our proposal to upgrade the quality of local marine light diesel with a view to reducing emissions from local vessels.

BACKGROUND

2. Marine vessels are the largest local air emission source. In 2011, local crafts and river vessels plying between Hong Kong and PRD ports contributed about 21%, 32% and 57% of the total emissions of sulphur dioxide (SO_2), respirable suspended particulates (RSP) and nitrogen oxides from the marine sector. Their emissions could affect the residential developments in the coastal areas. We need to reduce these emissions for better protection of public health.

3. Lowering the sulphur content of marine light diesel is an effective means to reduce the emissions of SO_2 and RSP by local vessels. To lead by example, the Government vessel fleet started using ultra-low sulphur diesel (ULSD) in end-2001, which has a sulphur limit of 0.005%, and have been using Euro V diesel (with a sulphur limit of 0.001%) since 2009. In 2010, we completed a trial of powering local ferries with ULSD. Although the trial showed that the switch was technically feasible, the fuel cost could be increased by $0.93 per litre (about 21%) at the time, mainly due to extra fuel handling costs for serving only a few vessels on trial. To avoid having additional fuel handling costs as a result of only requiring a segment of the local marine sector to use cleaner fuel and maximise the environmental benefits, we have proposed to adopt a blanket approach for upgrading the quality of local marine light diesel.

TECHNICAL FEASIBILITY STUDY

4. In May 2012, we set up a Working Group on Upgrading the Quality of Marine Light Diesel (WG), comprising representatives of local marine trades and relevant government departments, as well as a marine engineering expert from a local university, to examine the technical feasibility of upgrading the quality of local marine light diesel by reducing the limit on sulphur content from 0.5% to 0.05%. The latter is a common grade of diesel in the Asian fuel market. To address the concerns of some quarters of the local marine trade on the possible incompatibility of the proposed low sulphur diesel (LSD) with a sulphur limit of 0.05% with their vessel engines as well as the associated operational and maintenance implications, the WG agreed that these issues should be examined by powering two representative engine models, namely Gardner engine and Cummins engine with LSD.

5. We commissioned the University of Hong Kong (HKU) to conduct the technical study. The two engines were coupled with an alternating-current alternator for generating electricity and resistive load banks for varying output power demand. Tests were conducted with the engines running on both the current high sulphur diesel (HSD, with a sulphur limit of 0.5%) and the proposed LSD. The performance of engines (in terms of maximum power output and fuel consumption under various load conditions), the durability of engines (in terms of fuel lubricity, microscopic examination of fuel injectors and fuel pumps), and the change of engine oil properties after the durability test were examined. The study was completed in January 2013 and it confirmed the technical feasibility of powering local vessels with LSD. The key findings of the study are as follows –

(a) Maximum Power Output

The maximum power output of the engines could be maintained when using LSD. There was a minor drop (average -1.8%, range from -5.0% to +0.1%) for the Gardner engine but a minor increase (average +0.4%, range from -0.1% to +0.7%) for the Cummins engine. These small variations are insignificant and unnoticeable during operation.

(b) Fuel consumption under constant loading conditions

There was a small increase in specific fuel consumption (SFC) by

+1.1% (range from -1.3% to +2.9%) for Gardner engine and +1.3% (range from +0.8% to +2.1%) for Cummins engines when running on LSD. This is in line with the fact that the net calorific value of LSD is slightly lower.

(c) Fuel consumption for load variation during operation

The change in SFC for load variation during operation between the HSD and LSD was also small, about +1.4% (range from +0.8% to +3.0%) for Gardner engine and +1.3% (range from +1.2% to +1.5%) for Cummins engine.

(d) Wear and tear

No wear and tear in fuel injectors and pump was observed.

(e) Engine oil (lubrication oil) consumption and deterioration

The test recorded lower engine oil consumption, slower decrease in total base number and slower increase in viscosity when the engine ran on LSD. This means lower operating costs for LSD because the engine oil needs fewer replacement/replenishment.

Further details can be found in HKU's Executive Summary of the technical study at **Annex**.

OPERATIONAL COST IMPLICATIONS

6. If the fuel upgrade is conducted across the board, it would not create additional logistic overheads. Thus, for oil suppliers, any consequential increase in fuel cost arising from the switch to LSD will likely reflect the material cost difference between LSD and the current HSD. According to the fuel cost data from January 2012 to February 2013, the fuel cost differential[1] should be not more than HK$0.07/litre, or 1% based on current retail price of about HK$7/litre. An oil company advised that based on the fuel price trend in the past two months, the price gap could be even narrower. Moreover, Platts, a

[1] It refers to the average difference in Singapore free-on board (FOB) prices between these two fuels. FOB includes the transportation costs of fuel to the port of Singapore, the loading cost and the material cost.

leading global provider of benchmark price assessments for diesel market, has advised that the demand and supply of HSD in Asian market have been declining, whereas those of LSD have been growing. It is therefore expected that the price gap between HSD and LSD would keep narrowing down. On the other hand, as the use of LSD could give rise to a saving arising from the reduction in engine oil consumption, slower deterioration of engine oil, and engine performance improvement (because the exhaust gas is less acidic and less corrosive), part of the possible fuel cost increase would be offset.

ENVIRONMENTAL BENEFITS

7. A marine vessel operating on LSD emits about 90% less SO_2 and 30% less RSP than the one using HSD (with sulphur content of 0.5%). We expect that upon implementing the proposal, the estimated emission reduction will be 3,219 tonnes of SO_2 and 233 tonnes of RSP, i.e. a reduction in 19% and 10% respectively of the emissions from the marine sector in 2011. This will contribute toward an improvement to ambient air quality and reduced health risks of the population, especially in the coastal areas.

THE PROPOSAL

8. Following international practices and making reference to oil companies' practice, we propose requiring that for fuel that is put on sale, supply or distribution on Hong Kong market for use by vessels, it shall not contain sulphur more than 0.05% by weight. For other fuel quality parameters, we will retain the international specifications, viz., either –

(a) the specifications of ISO 8217; or

(b) the gasoil specifications of Platts[2], which are being used by the majority of the local oil companies for sourcing marine light diesel for the local market.

Both of them are currently adopted by the oil companies and their retention will

[2] ISO 8217 refers to DMA grade in Table I of ISO 8217, issued by the International Organisation for Standardisation. Platts refers to 0.05% sulphur gasoil as defined in FOB Singapore gasoil/ diesel specifications of Specifications and Methodology Guide for Asian oil products issued by Platts.

ensure the vessels will receive same quality of diesel after the sulphur content is tightened. Marine light diesel trading activities that do not involve sale, supply or distribution (such as import for re-export, stock movement within the same oil company) are not subject to the control proposal. At present, there is no regulation governing the standard for marine light diesel sold in Hong Kong.

9. We also propose to set the offence and penalty regime by making reference to similar provisions and arrangements under the Air Pollution Control (Motor Vehicle Fuel) Regulation (Cap. 311L) for cases of non-compliance.

CONSULTATION

10. We have consulted relevant stakeholders (including vessel operators and oil companies) on our proposal and have taken their views into account when drawing up the above proposal. The oil companies have confirmed the availability of marine light diesel complying with the proposed specifications and will make preparations to meet the proposed implementation timetable. The vessel operators have agreed to the findings and conclusion of the technical trial. However, they are concerned about the possible additional cost implication of using LSD. Some operators query that the current fuel price difference could be as much as $1/litre despite the minimal difference in the import prices. Some of them have raised the following suggestions:

(a) the Government should ensure the oil companies will not increase the diesel price upon the introduction of LSD. If unavoidable, the diesel price adjustment should not be higher than the import price premium of LSD over HSD;

(b) the Government should consider opening the fuel supply market to promote greater competition and hence more reasonable fuel prices;

(c) as engine replacement could help further reduce the emissions of other air pollutants, the Government should also consider this option and provide adequate subsidies to the trade.

11. Hong Kong is a free market economy. Oil companies can determine fuel prices taking account of market situations including international fuel price

fluctuations. As the proposed across-the-board fuel upgrade will cause no extra fuel handling cost, we expect that the actual price difference should essentially be the same as that of the import prices. Upgrading diesel quality can bring substantial and immediate benefits to the air quality in the coastal areas, many of which now have many residential developments.

12. We will consult the Advisory Council on the Environment (ACE) in April 2013 on the proposal. To help the vessel operators and oil suppliers to better understand the implementation plan of our proposal, we will continue to engage them through briefings and discussions.

LEGISLATIVE TIMETABLE

13. Subject to the support from this Panel and ACE, we aim at tabling the new regulation for the Legislative Council's scrutiny in late 2013, with a view to implementing the control requirements in 2014.

ADVICE SOUGHT

14. Members' views are sought on the regulatory proposal as set out in paragraphs 8 to 9.

Environmental Protection Department
March 2013

The University of Hong Kong
香港大學

Marine Engine Tests on Laboratory Setting

Executive Summary

Submitted to: Environmental Protection Department
HKSAR Government

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Date: 14th March 2013

Executive Summary of Marine Engine Tests on laboratory Setting

Background

Marine vessels emissions have been increasing over the past decades and become the top emitter of sulphur dioxide (SO_2), respirable suspended particulates (RSP) and nitrogen oxides (NOx) emissions in Hong Kong. The Hong Kong SAR Government has studied ways to reduce the marine emissions. One approach is to improve the quality of locally supplied marine diesel to reduce emissions from local and river vessels. The Environmental Protection Department (EPD) of the HKSAR Government proposed to reduce the sulphur limit of marine light diesel from 0.5% to 0.05%, which would result in a corresponding reduction of SO_2 and RSP emissions of individual vessel by about 90% and 30% respectively. A Working Group (WG) was formed in May 2012 with members from government officials of various departments, local vessel operators' representatives and experts in academia. The 1st and 2nd WG meetings agreed to conduct engine test on two commonly in-use marine engines using the high sulphur diesel (HSD, maximum 0.5% sulphur content by mass) and low sulphur diesel (LSD, maximum 0.05% sulphur content by mass) fuel in order to confirm the compatibility and performance of the LSD in existing vessel engines.

The Department of Mechanical Engineering at the University of Hong Kong was commissioned by the EPD in July 2012 to conduct a study on "Marine Engine Tests on Laboratory Setting" as a means to address the concerns of the WG members. The study employed tailor-made laboratory setup for evaluating the performance of two marine type diesel engines under different simulated working conditions. Methodologies of the test had been presented and endorsed in the 2nd WG meeting on 5 June 2012. An interim report summarising the preliminary results obtained from testing the Gardner 6LXB engine was issued to EPD in January 2013. This Executive Summary of the final report summarizes all the results obtained from testing the two selected in-use marine type diesel engines i.e. Gardner 6LXB and Cummins NTA855(M).

Objectives and Scope of Works

(1) To conduct tests for LSD for assessing the following for the two in-use marine engines under controlled laboratory environment:

(a) the performance in terms of maximum engine power output and fuel consumption at various load conditions; and

(b) the durability in terms of fuel lubricity and engine compatibility, which are based on measured fuel lubricity, microscopic examination of fuel injectors and pump, and analysis of used engine oil.

(2) To conduct the same tests for HSD as base case for comparison with LSD.

Results

A. Gardner Engine

(1) Diesel Fuel Analysis

HSD and Euro V diesel (EVD, maximum 10 parts per million sulphur content by mass) were provided by the fuel supplier of the government. LSD for testing was produced by blending one part of HSD with 10 parts of EVD by volume. Certificates of Quality (CoQ) for HSD and EVD provided by the fuel supplier and tested by an independent laboratory confirmed diesel compliance to specifications. In particular, the net calorific value (NCV, kJ/L) of the LSD was lower than the HSD by 1.6% and 2.2% respectively for the two analysed samples obtained during the HSD and LSD Performance Tests.

(2) Performance Test

(a) Maximum engine power

The maximum output power between the LSD and HSD fuels under the following four cases: before the HSD durability (baseline 1), after the HSD durability, before the LSD durability (baseline 2), and after the LSD durability can be found in the table below:

Max. power output	Base-line 1	After 200-hr of HSD Durability	Base-line 2	After 200-hr of LSD Durability	Overall average
HSD (kW)	106.2	116.3	115.3	117.7	113.9
LSD (kW)	104.9	115.0	109.5	117.8	111.8
% change LSD Vs HSD	-1.3%	-1.1%	-5.0%	+0.1%	-1.8%

As can be seen from the above table, the percentage change in maximum power varies from +0.1% to -5% with an overall average -1.8%. This drop in maximum power matched with the decrease in NCV for the LSD Vs HSD (1.9%).

(b) Specific fuel consumption

Specific fuel consumptions (SFC) at various engine loadings were determined. Sixth different engine loading conditions were tested, respectively 100% (i.e. 89 kW), 85%, 75%, 50%, 25% loading and a load cycle from 83% to 87%. The comparison of SFC between LSD and HSD under different loading conditions is shown in the table below for the following three stages: Baseline, after 200-hr Durability Test without engine oil replacement, and after 200-hr Durability Test with engine oil replacement.

Before and after the HSD Durability Test: Engine loading condition	Baseline (1^{st})	After 200-hr	After 200-hr & engine oil replacement	Average
100% LSD Vs HSD	-1.3%	+0.7%	+1.4%	-0.1%
85% LSD Vs HSD	+0.1%	+0.6%	+0.9%	+0.4%
75% LSD Vs HSD	+1.2%	+0.6%	+1.1%	+1.0%
50% LSD Vs HSD	-0.3%	+1.9%	+1.2%	+0.6%
25% LSD Vs HSD	-1.0%	+2.0%	+1.2%	+0.3%
Load Cycle (83% to 87% load) LSD Vs HSD	+0.9%	+1.0%	+1.3%	+1.0%
				Overall average: +0.5%

Before and after the LSD Durability Test: Engine loading condition	Baseline (2^{nd})	After 200-hr	After 200-hr & engine oil replacement	Average
100% LSD Vs HSD	+1.1%	+2.6%	+2.9%	+1.9%
85% LSD Vs HSD	+1.2%	+2.7%	+2.6%	+1.9%
75% LSD Vs HSD	+1.1%	+2.6%	+2.5%	+1.8%
50% LSD Vs HSD	+1.1%	+1.9%	+2.0%	+1.5%
25% LSD Vs HSD	+0.6%	+1.3%	+1.6%	+1.0%
Load Cycle (83% to 87% load) LSD Vs HSD	+0.8%	+2.7%	+3.0%	+1.8%
				Overall average: +1.7%

Before (1^{st} baseline) and after the HSD Durability Test, the average SFC for LSD varied from

-0.1% to +1.0% with an overall average of +0.5% for all the loading conditions. Similarly, before (2nd baseline) and after the LSD Durability Test, the SFC for LSD varied from +1.0% to +1.9% with an overall average of +1.7% for all the loading conditions. Thus, there is a slight increase in the % increase of SFC for the LSD durability test, which is consistent with the larger reduction in NCV (2.2% compared to1.6%).

(3) Durability Test

(a) Basic operational data

Durability Test was conducted first for HSD then LSD, both maintained for running 200 hours and at 68 kW constant power output, with 33.5 and 23.0 litre engine oil re-filled to replenish consumption. The large difference of 10.5 litres in engine oil consumption between HSD and LSD may be due to the following reasons:

(i) Larger amount of engine oil leakage and poorer control of engine oil addition at the beginning of the HSD Durability Test;

(ii) Engine run-in effect that consume more HSD;

(iii) Inherent feature of using LSD. Some researchers found that LSD would produce less sulphur dioxide than HSD during the combustion, which would be transformed to sulphuric acid. This would lead to less severe pitting and improved cylinder surface finish, hence lower engine oil consumption.

(b) Fuel injector test

Fuel injectors opening pressures were tested before and after the trial for each of the test fuels and fuel atomization patterns observed to ensure proper fuel delivery before and after the HSD and LSD Durability Test. The results obtained indicated that the opening pressures of all the injectors complied with the limit stipulated in the Gardner's operation and maintenance instruction manual demonstrating that the fuel deliveries are normal during the two durability tests. Atomization patterns of injector spray for all the six injectors were also found satisfactory for both HSD and LSD.

(c) Fuel injection pump test

Fuel injection pump was tested before and after the HSD and LSD Durability Tests. The test on maximum fuel setting and fuel delivery quantities of injection pump per 200 strokes @600 rpm were measured by standard test equipment, and was manually observed and recorded. All the results were found to fall within ± 0.2 c.c., within the sensitivity range of the combined test equipment uncertainty and human error.

Both fuel injector and pump test results are consistent with the observation of injector nozzles, hollow piston valves, pump plungers and delivery valves by SEM and LPEM, and the measured results of fuel lubricity being well below 460 μm.

(d) Engine Oil Analysis

Engine oil samples were taken at 0, 100 and 200 hours of the HSD and LSD Durability Tests for chemical analyses and the results are shown below for the HSD and LSD Durability Test:

HSD Durability Test: Test Parameter	Spec.	0-hr	100-hr	200-hr	Difference (200hr -0hr)
Viscosity, cSt @ 100°C	14.1	14.0	14.2	14.7	+0.7
Total Base Number (mg KOH/g)	10.1	9.2	8.0	7.8	-1.4
Wear Elements (ppm): Ag, Mo, Ni, SN which have less than 4 ppm are not shown					

Al	0	3	5	5	+2
Cr	0	7	18	22	+15
Cu	0	5	9	9	+4
Fe	0	18	19	19	+1
Pb	0	2	4	5	+3

LSD Durability Test: Test Parameter	Spec.	0-hr	100-hr	200-hr	Difference (200hr -0hr)
Viscosity, cSt @ 100°C	14.1	14.1	14.3	14.6	+0.5
Total Base Number (mg KOH/g)	10.1	8.8	8.3	8.7	-0.1
Wear Elements (ppm): Ag, Mo, Ni, SN which have less than 4 ppm are not shown					
Al	0	1	3	4	+3
Cr	0	2	13	18	+16
Cu	0	1	3	5	+4
Fe	0	4	11	16	+12
Pb	0	1	2	3	+2

The following are the observations from the engine oil analysis:

(i) Viscosity

There is an increase in viscosity over the 200 hours' Durability Test and the increase is 5.0% and 3.5% for HSD and LSD respectively. This means that the viscosity increase faster for the HSD case.

(ii) TBN

There is a rather big reduction in TBN over the 200 hours' test period for the HSD (15%) but only a minor reduction of 1% for the LSD. A plausible explanation is that additive replenishment (i.e. topping off the oil) is replacing sufficient additive to offset the amount consumed by much lower quantity of sulphuric acid generated from the LSD than the HSD combustion. Nevertheless, both TBN values at 200-hr for HSD and LSD are still within normal range. According to the engine oil manufacturer, engine oil need to be changed when the TBN values drops below half of the original values. Thus, the lower TBN depletion rate for LSD should benefit the engine operation by possible reduction of engine oil changing frequency. Such benefit would become more since LSD consumes less engine oil.

(iii) Elemental analysis

There is a general increase in metal concentrations in the engine oil over the 200-hr testing due to engine wear. Incremental metal concentrations due to wear for HSD and LSD were more or less similar except higher iron for LSD.

(e) Scanning Electronic Microscope (SEM) Examination

To investigate whether there is wear and tear problem caused by fuel flow, all components of fuel injectors and pump set of the Gardner engine that may be subject to wear and tear due to fuel lubricity were purchased new and examined before and after the Durability Tests. These components include injector nozzles, hollow piston valves, pump plungers and delivery valves.

The SEM photos taken showed that the shapes and sizes of the nozzles remain the same after the 200-hr Durability Tests for both HSD and LSD cases. Some deposits found inside the nozzles of both HSD and LSD was identified to be mainly carbon and oxygen, which may come from the unburnt fuel. In general, based on the SEM observations, no abnormal finding and discrepancy could be identified for both the HSD and LSD cases.

(f) Low Power Electronic Microscope (LPEM) Examination
The surface finishes of the plungers were compared under LPEM for both the HSD and LSD cases. As can be seen from the photos taken, the surface finishes of the examined component did not exhibit any significant changes before and after the Durability Test for both HSD and LSD. The LPEM investigation indicated that there are no significant differences in the tear and wear characteristics for both the HSD and LSD cases.

B. Cummins Engine
(1) Diesel Fuel Analysis
The two test fuels (HSD and LSD) examined by the independent laboratory matched with the CoQ provided by the fuel supplier. The test results indicate that the percentage difference in NCV between LSD and HSD are -1.5% and -2.2% for the two batches of samples with an average of -1.8%.

(2) Performance Test
(a) Maximum engine power
The variation in maximum engine output power between the LSD and HSD fuels are shown in the table below:

Max. power output	Base-line 1	After 200-hr of HSD Durability	Base-line 2	After 200-hr of LSD Durability	Overall average
HSD (kW)	300.7	301.2	290.2	292.6	296.4
LSD (kW)	302.7	303.0	289.9	293.2	297.5
% change LSD Vs HSD	+0.7%	+0.6%	-0.1%	+0.2%	+0.4%

Despite a small reduction in NCV of the LSD fuel, there is a small percentage increase in maximum power, which varies from +0.7% to -0.1% with an overall average of +0.4%..

(b) Specific fuel consumption
Six different engine loading conditions were tested, respectively 100% (i.e. 196 kW), 85%, 75%, 50%, 25% loading and a load cycle from 83% to 87%. The comparison of SFC between LSD and HSD under different loading conditions is shown in the table below for the following three cases: Baseline, after 200-hr Durability Test without engine oil replacement, and after 200-hr Durability Test with engine oil replacement.

Before and after the HSD Durability Test: Engine loading condition	Baseline (1^{st})	After 200-hr	After 200-hr & engine oil replacement	Average
100% LSD Vs HSD	+1.0%	+1.2%	+0.8%	+1.0%
85% LSD Vs HSD	+1.6%	+1.5%	+1.6%	+1.6%
75% LSD Vs HSD	+1.6%	+1.4%	+1.5%	+1.5%
50% LSD Vs HSD	+1.2%	+1.3%	+1.3%	+1.3%
25% LSD Vs HSD	+1.4%	+1.3%	+1.1%	+1.3%

Load Cycle (83-87%) LSD Vs HSD	+1.4%	+1.5%	+1.2%	+1.3%
			Overall average:	+1.3%

Before and after the LSD Durability Test: Engine loading condition	Baseline (2nd)	After 200-hr	After 200-hr & engine oil replacement	Average
100% LSD Vs HSD	+1.4	+1.7	+1.7	+1.5
85% LSD Vs HSD	+1.2	+2.0	+1.9	+1.6
75% LSD Vs HSD	+0.8	+2.1	+1.9	+1.4
50% LSD Vs HSD	+1.0	+2.1	+1.9	+1.5
25% LSD Vs HSD	+0.9	+1.6	+1.9	+1.4
Load Cycle (83% to 87%) LSD Vs HSD	+1.2	+1.4	+1.5	+1.3
			Overall average: +1.4%	

All the SFC results obtained were normal and fell within the range provided in the engine manual. Same as the Gardner engine, the variation in SFC with and without engine oil replacement were very similar in magnitude indicating that the engine oil replacement did not affect SFC significantly. Before (1st baseline) and after the HSD Durability Test, the SFC for LSD over HSD varied from +1.0% to +1.6% with an overall average of +1.3% for all the loading conditions. Before (2nd baseline) and after the LSD Durability Test, the SFC for LSD over HSD varied from +1.3% to +1.6% with an overall average of +1.4% for all the loading conditions. The slight increase (+1.3% to +1.4%) in SFC for LSD over HSD is consistent with the reduced NCV (-1.8%, LSD Vs HSD) as mentioned in the Diesel Fuel Analysis.

(3) Durability Test

(a) Basic operational data

Durability Test was conducted first for HSD then LSD, both maintained for running 200 hours and at 186 kW constant power output. Different from the Gardner engine tested, the Cummins engine completed both the 200-hr HSD and LSD Durability Tests without the need of replenishing engine oil.

(b) Fuel injector test

The amount of fuel injection of all the six injectors complied with their operation limit demonstrating that the fuel deliveries were normal before and after the two Durability Tests. Atomization patterns for all the six injectors were found satisfactory for both HSD and LSD.

(c) Fuel metering pump check

Fuel injection pump was tested before and after the trial for HSD durability and LSD Durability Tests. All the results were found to fall within ± 3% considered to be within the sensitivity range of the combined test equipment uncertainty and human error. Thus, there was no significant difference before and after both the HSD and LSD Durability Tests.

Both fuel injector and pump test results were consistent with the observation of injector nozzles, metering pump plungers and fuel injector plungers by SEM and LPEM, and measured results of fuel lubricity being well below 460 µm.

(d) Engine Oil Analysis

The results of the engine oil analysis at 0, 100 and 200 hours for HSD and LSD Durability Tests are shown in the tables below:

Test Parameter (HSD Durability Test)	Spec.	0-hr	100-hr	200-hr	Change (200hr -0hr)
Viscosity, cSt @ 100°C	15.5	14.9	14.7	15.3	+0.4
Total Base Number (mg KOH/g)	10	11.2	10.7	10.4	-0.8
Wear Elements (ppm): Ag, Ni, SN which have less than 4 ppm are not shown					
Al	0	1	1	1	0
Cr	0	0	0	1	+1
Cu	0	1	3	5	+4
Fe	0	3	17	27	+24
Pb	0	0	0	2	+2

Test Parameter (LSD Durability Test)	Spec.	0-hr	100-hr	200-hr	Change (200hr -0hr)
Viscosity, cSt @ 100°C	15.5	15.0	14.8	15.2	+0.2
Total Base Number (mg KOH/g)	10	11.4	11.5	11.6	+0.2
Wear Elements (ppm): Ag, Ni, SN which have less than 4 ppm are not shown					
Al	0	1	1	1	0
Cr	0	0	0	0	0
Cu	0	0	1	2	+2
Fe	0	2	12	18	+16
Pb	0	0	0	1	+1

The following are the observations from the engine oil analysis:

(i) Viscosity

There was an increase in viscosity over the 200 hours' Durability Test and the increase is +2.7% and +1.3% for HSD and LSD respectively showing that the rate of viscosity increase for LSD was lower.

(ii) TBN

There was a significant reduction in TBN over the 200 hours' test period for the HSD (7.1%) but the TBN values for LSD could be maintained (+1.8%). Nevertheless, the TBN values for HSD were still within normal range. As mentioned above, engine oil need to be changed when the TBN values drops below half of the original values. Thus, the non-depleted TBN for LSD would benefit the engine operation by possible reduction of engine oil changing frequency. As the extent of this reduction would also depend on the viscosity deterioration rate of the engine oil, it is likely that the benefit for LSD, which has a lower viscosity deterioration rate as shown in (i) above, should even be greater.

(iii) Elemental analysis

There is a general increase in metal concentrations in the engine oil over the 200-hr testing due to engine wear. The incremental metal concentrations due to wear for HSD and LSD were more or less similar except higher iron for HSD.

(e) Scanning Electronic Microscope (SEM) Examination
The SEM photos taken showed that the shapes and sizes of the nozzles remained the same after the 200-hr durability tests for both HSD and LSD cases. Some deposits were found inside the nozzles of both HSD and LSD, which was identified to be mainly carbon and oxygen, and most likely come from the unburnt fuel. In general, based on the SEM observations, no abnormal finding and discrepancy could be identified for both the HSD and LSD cases.

(f) Low Power Electronic Microscope (LPEM) Examination
The surface finishes of the metering pump plungers and fuel injector plungers were compared for both the HSD and LSD cases. The LPEM examination showed that the surface finishes of the examined component did not exhibit any significant changes before and after the Durability Test for both HSD and LSD. The LPEM investigation indicated that there are no significant differences in the wear/tear characteristics for both the HSD and LSD cases.

Conclusions

(a) The maximum power of the Gardner and Cummins engine can be maintained for LSD with respect to HSD. There was a very minor drop (-1.8%, from -5.0% to +0.1%) for the Gardner but also a minor increase (+0.4%, from -0.1% to +0.7%) for the Cummins engines respectively. However, these small variations are insignificant and unnoticeable during actual operation.

(b) There was a small increase in specific fuel consumption (SFC) under constant load conditions of +1.1% (from -1.3% to +2.9%) and +1.3% (from +0.8% to +2.1%) for the Gardner and Cummins engines respectively for LSD wrt HSD, which is in line with the small net reduction in calorific values of the LSD wrt HSD.

(c) The change in SFC for load variation during operation is also small between the HSD and LSD, about +1.4% (from +0.8% to +3.0%) for Gardner and +1.3% (from +1.2% to +1.5%) for Cummins.

(d) Error for maximum power determination and % SFC change was estimated to be ±4.4% and ±1.7% respectively, showing high accuracy for the results obtained.

(e) From the Durability Test, there was not much difference of fuel injectors and pump wear due to fuels between HSD and LSD after the 200 hours' operation, as indicated from the fuel injector and pump performance tests, and microscopic examinations (SEM and LPEM).

(f) There were some changes in engine oil characteristics indicating benefits when the fuel was switched from HSD to LSD: slower decrease in TBN and slower increase in viscosity. However, the wear elements in the engine oil did not show significant difference between HSD and LSD.

(g) There was an indication of lower engine oil consumption for LSD during the Gardner engine testing, which however, is not obvious during the Cummins engine testing.

(h) The observations from the engine oil consumption and chemical analysis indicate some advantages of the LSD fuel over HSD, which is in line with the USEPA's claimed benefits on LSD.