1. INTRODUCTION

The objectives upon which engine designers are now concentrating in their development of new power units include emissions control, power density, engine durability, extension of service intervals and improved fuel economy. Many of these key objectives are related to the condition of the lubricating oil.

In response to changes in economic and environmental circumstances, conservation of engine lubricating oil is also becoming increasingly important. These savings are being achieved through reductions in oil consumption and the implementation of extended oil drain periods, as a result of which modern oils must work harder, resist degradation for longer periods and retain greater volumes of fixed insolubles.

It is also known that oil removed from the inside walls of piston cylinders during the combustion process is a major contributor to particulate emissions, so that reduced piston ring gaps and minimised rates of oil consumption are essential for low emission engines.

The summary effect of lower oil consumption and extended service intervals is that contaminated oil remains in engine oil sumps for longer periods. Unless the cleanliness of this oil is maintained by effective oil filtration the resulting engine component wear will, over time, decrease engine operating efficiency and increase exhaust emissions.

The largest constituent of lubricating oil contaminant found within a diesel engine is carbon soot (1). The introduction of exhaust gas recirculation (EGR) to reduce NOx emissions increases the soot loading within the oil, and can cause problems relating to an acceleration in oil degradation and greater engine wear, especially in the valve train (2). Engine designers regard soot reduction as one of their key objectives to meet future requirements for both extended service intervals and emissions reduction.

Many engineers believe that, to be able to meet future targets for exhaust emissions and engine life using only standard filtration methods, oil changes would need to be more frequent or sump volumes made bigger. Both these options are unfavourable as they increase operating costs. Alternatively, to meet future economic and environmental requirements methods of maintaining oil cleanliness must be considered.

Environmental concern for the safe and efficient disposal of all engine waste products is growing worldwide. Landfilling of oil filter elements is already prohibited in many US states, and similar legislation is likely to be effected in the near future for Europe and other parts of the world. In addition to increases in oil change intervals, engine users will demand the introduction of cleanable filtration systems in order to control their operating costs.

This paper describes an engine test programme performed to study the effects of a by-pass self-driven centrifugal lubricating oil cleaner (centrifuge) on a modern low emission automotive diesel engine. The results concern all aspects of oil condition throughout a series of extended service intervals. In addition, results involving the application of a by-pass centrifuge in conjunction with a full flow cleanable metallic screen are also presented.

2. THE ENGINES AND TEST OBJECTIVES

Previous papers concerning the centrifuge have examined results achieved through accelerated wear tests (3,4). These demonstrated effectively that the application of a by-pass centrifuge, in addition to the full flow filter, can substantially decrease component abrasive wear rates by removing the very small abrasive particles that are missed by full flow filtration.

In response to the future requirements of diesel engine manufacturers, the main objective of the tests described herein was to assess the performance of three different lubricating oil filtration systems by monitoring oil condition throughout various operational intervals, using a standard engine test cycle.

Three 2.5 litre diesel engines were tested, all with four cylinders and direct injection, intercooled and turbocharged. In addition the engines were designed for low exhaust emissions, incorporating an EGR system.

The oil filtration systems adopted were as follows:

Engine 1: Standard cartridge full flow filter (15 micron normal mesh)

Engine 2: Standard cartridge full flow filter plus a by-pass oil cleaning centrifuge

Engine 3: 45 micron full flow metal screen plus a by-pass oil cleaning centrifuge

The main objective for the testing of Engine 3 was to demonstrate that the introduction of a 45 micron full flow screen, in conjunction with a by-pass centrifuge, had no detrimental effects on oil condition when operated over an extended oil change interval.

Throughout the test programme, the contaminant removed by the centrifuges fitted to Engines 2 & 3 was analysed physically and chemically with the objective of gaining an understanding of the type, quantity and size range of the contaminant particles captured. Furthermore, on completion of the test on Engine 3 the metallic full flow screen was also analysed physically to assess its performance.

3. THE CENTRIFUGAL OIL CLEANER

The by-pass centrifuge selected for application to Engines 2 & 3 (model GF016) has a 0.16 litre contaminant holding capacity; the mass of carbon soot that can be stored in the rotor is 200g. The principle of operation, as displayed in Fig 5.1, is relatively simple. The rotating element (rotor) within the centrifuge is driven by pump pressure oil flowing through two tangential nozzles in its base. The oil passing through the rotor is subjected to a centrifugal force of greater than 3000g, which causes contaminant particles to migrate outwards and form a dense cake on the inner wall of the rotor (Fig 5.2).

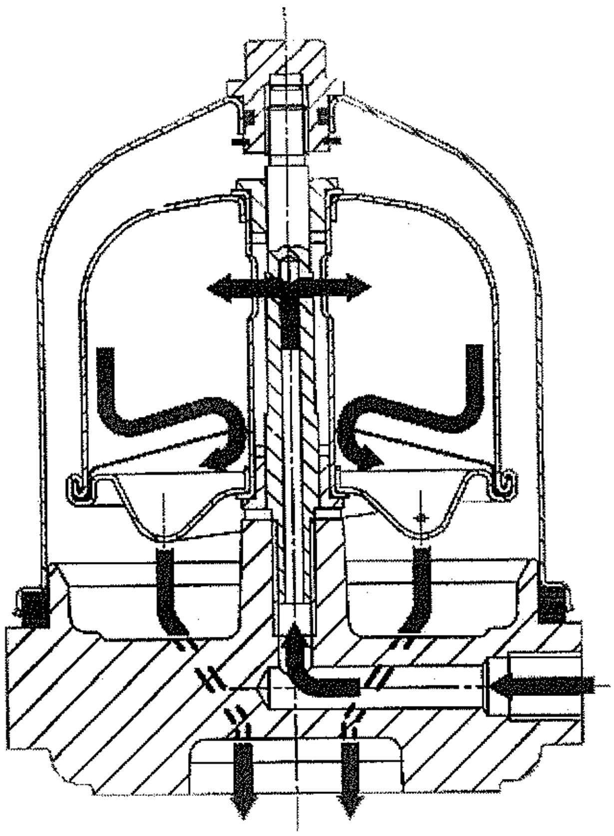

Fig 5.1 Centrifugal Oil Cleaner - Principle of Operation

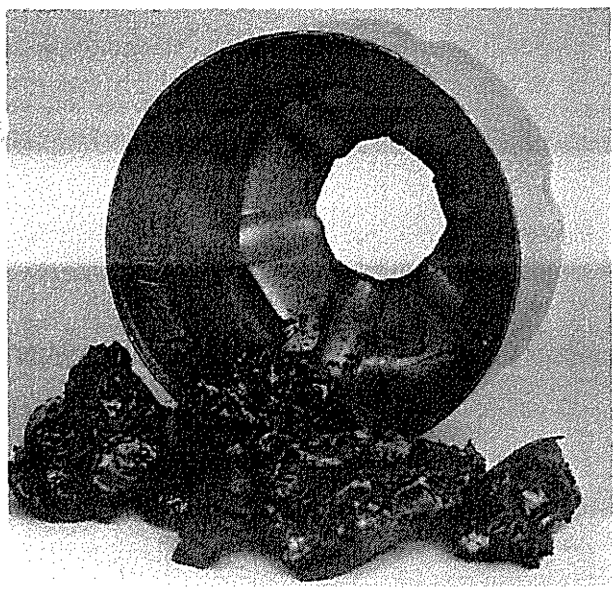

Fig 5.2 Section of Rotor Showing Level of Contaminant Removed from Engine 3 after 384 Hours

For both Engines 2 & 3 the centrifuge was fitted as a by-pass filter in conjunction with a standard full flow cartridge or metal screen. On leaving the centrifuge the oil was gravity drained directly back into the engine sump (Fig 5.3).

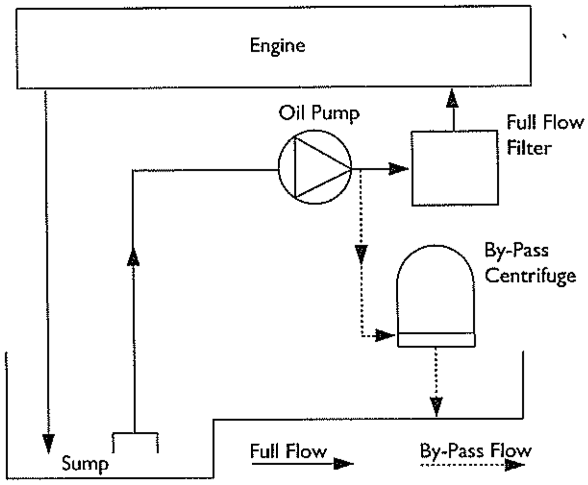

Fig 5.3 Principle of By-Pass Filtration

During the engine tests the oil pressure entering the centrifuge was between 3.0 and 3.5 bar; the centrifuge rotor speed averaged around 7000 rev/min. The oil capacity for the engines tested was 7.11 litres and in addition an extra 2.66 litres was required for the engine test cell pipework and cooler.

The rate of by-pass flow was such that 7.11 litres would be processed in the centrifuge between 20 and 30 times per hour, depending on engine speed and oil temperature.

The rate at which oil is circulated through the centrifuge on an engine of this size is considerably higher than that of centrifuges fitted to larger heavy duty diesel engines. This is beneficial, as it increases the probability of a contaminant particle passing through the centrifuge and being extracted (5).

4. THE FULL FLOW METAL SCREEN

The primary function of a full flow filter is to process all the oil supplied to the engine, protecting the lubricated parts from large abrasive contaminant particles. The filtration level of a full flow filter is restricted because of a number of factors including high flow requirement, minimal pressure drop across the filter element and physical size; filtration below 15 microns is not normally achieved.

A by-pass centrifuge used in combination with a cleanable metal screen offers a simple alternative to paper element filters (Fig 5.4). The screen fitted to Engine 3 was manufactured from 45 micron (nominal pore size) stainless steel mesh. In this combination arrangement, the role of the centrifuge is to remove all of the fine contaminant capable of causing long term wear, including carbon soot, whereas the metal screen protects the engine from large particles likely to cause catastrophic engine failure.

Due to the inherent ability of a centrifuge rotor to effectively compact and store over five times the volume of oil contaminant that can be stored by an equivalent sized paper element filter, it is theoretically possible to design a 'fit-for-life' filtration system based upon a centrifuge and

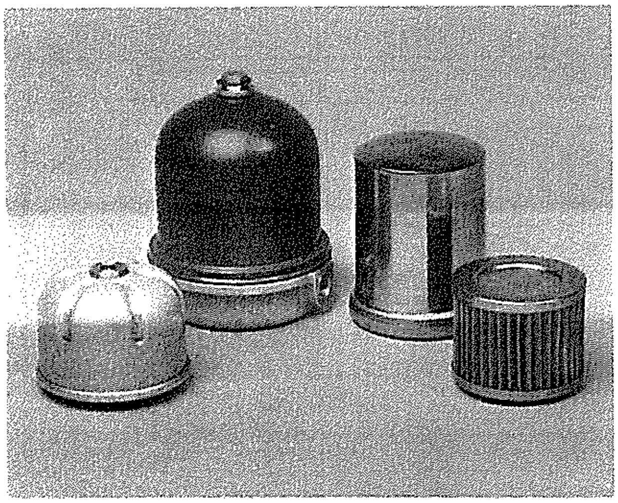

Fig 5.4 Model GF016 Centrifuge plus Full Flow Screen

screen combination unit. Part of these engine tests was therefore designed to evaluate the amount of dirt produced by the engine, to be consequently stored by the rotor throughout a very extended oil drain interval. This information, once generated, may be used to design an oil filtration system possibly capable of maintaining oil condition up to 100,000 km.

5. ENGINE TEST PROCEDURE

An EGR durability test cycle was adopted throughout the complete engine test programme. Each cycle was of three hours duration and contained three stages:

Stage 1: 1800 rev/min, 120 Nm torque for 30 seconds

1800 rev/min, max. fuel (full load) for 30 seconds

Above repeated for 60 minutes

Stage 2: 2500 rev/min, 120 Nm torque for 30 seconds

2500 rev/min, max fuel for 30 seconds

Above repeated for 60 minutes

Stage 3: 4000 rev/min, max fuel for 60 minutes

It should be noted that the oil drain interval specified by the original equipment manufacturer for the EGR test cycle is 100 hours; for the test programme adopted this interval was extended initially to 192 and then to 384 hours.

Prior to the tests Engines 1 & 2 completed a specified 15 hour run-in cycle, after which both engines were drained and re-filled with fresh oil. They were operated for a total of 1152 hours, during which period the oil, the full flow cartridge filter and the centrifuge rotor (Engine 2) were changed at the intervals displayed in Table 5.1.

In order to assess the comparability between Engines 1 & 2 the first 192 hour service interval was completed using only standard full flow filtration. Thus the centrifuge fitted to Engine 2 was non-operational during this period.

Engine 3 was subjected to a limited run-in cycle of 3 hours, after which it completed 384 hours of operation

OPERATION (h)	OIL & FILTER CHANGE (h)	SERVICE INTERVAL (h)
0 - 192	192	192
192 - 384	384	192
384 - 576	576	192
576 - 768	768	192
768 - 1152	1152	384

Table 5.1 Service Intervals - Engines 1 & 2

using the specified EGR test cycle. It is important to note that this engine was not flushed through after manufacture to remove built-in contaminant; furthermore the oil was not changed after the run-in cycle but was retained throughout the 384 hours.

The purpose of not changing the oil after run-in was to maximise the amount of engine build and run-in contaminant present in order to test fully the capability of the screen/centrifuge combination.

The three engines were installed within a computer controlled test cell, allowing for on-line measurement of a number of important engine variables. This facility ensured that test conditions were maintained throughout.

The lubricating oil used for the tests was:

Manufacturer:BP

Grade:15W40

Reference:L93/10038/XF3544

Two 50ml oil samples were taken from each engine at regular intervals (Table 5.2).

	OPERATIONAL PERIOD (h)	SAMPLING PERIOD (h)
Engines 1 & 2	0 - 768	Every 24
Engines 1 & 2	768 - 1152	Every 48
Engine 3	0 - 384	Every 48

Table 5.2 Oil Sampling Intervals

In order to minimise the amount of top-up oil added throughout a service interval, fresh oil was introduced only after the minimum allowable sump level was reached. This level was then maintained daily by adding a measured quantity of fresh oil.

6. OIL ANALYSIS TECHNIQUES

Oil samples taken at specified intervals from Engines 1, 2 & 3 were analysed within two independent laboratories. The oil analysis procedures adopted were selected to provide a detailed set of results relating to oil condition. In addition to measurements for viscosity, Total Base Number (TBN), Total Acid Number (TAN), nitration & dispersency, the following other analysis techniques were used.

6.1 Spectroscopy

Selected microscopic particles suspended within the oil are identified and measured in parts per million (ppm). The elements detected can be split into three groups, ie wear metals, ingested contaminant and additive.

The two main types of spectroscopy are Inductively Coupled Plasma (ICP) and Rotating Disk Electrode (RDE). RDE Spectroscopy, which identifies particles up to about 12 microns in size, was used for the engine test programme.

6.2 Total Insolubles (modified blotter spot)

A known volume of oil was spotted on to special paper and allowed to spread. Modern image analysis equipment was used to examine the oil spread and provide a reliable value for total insoluble content.

6.3 Pentane Insolubles

The oil sample is dissolved within the solvent Pentane and then filtered through a 0.3 micron millepore. The contaminant captured by the millepore is measured as a percentage of the total sample size (% wt).

The Pentane insolubles value depicts the level of soot and traces of wear metals, of a size greater than 0.3 microns, present within the oil sample.

6.4 Light Extinction Measurement (LEM)

The LEM technique is a reliable means of detecting and measuring dispersed soot within diesel engine oils (6).

The soot measurement is determined directly from the oil sample, unlike other analysis techniques that rely on solvent dilutions or centrifugal separation to release the particulate. The initial results are achieved in LEM units which are directly convertible into a percentage of the soot present (% mass).

It is possible to calculate from an LEM result an approximate value for the total mass of soot (grams) in circulation within the engine, for example:

LEM Result for Engine 2 at 192 hours:	1.76%
Total oil capacity:	9.77 litres
Oil density:	0.9 g/cm³
Total mass of oil in circulation:	0.9 x 9770 = 8793 g
Mass of soot in Engine 2 at 192 hours:	0.0176 x 8793 = 154.76 g

7. 192 HOUR SERVICE INTERVAL - SUMMARY OF RESULTS

The oil and sludge analysis results obtained for Engines 1 & 2 operating throughout 768 hours can be summarised as follows.

On average the centrifuge fitted to Engine 2 removed 69.8g of oil contaminant during a service interval of 192 hours (Fig 5.5), of which approximately 53% was attributed to engine clogging soot.

Soot contamination within the oil of Engine 2 was

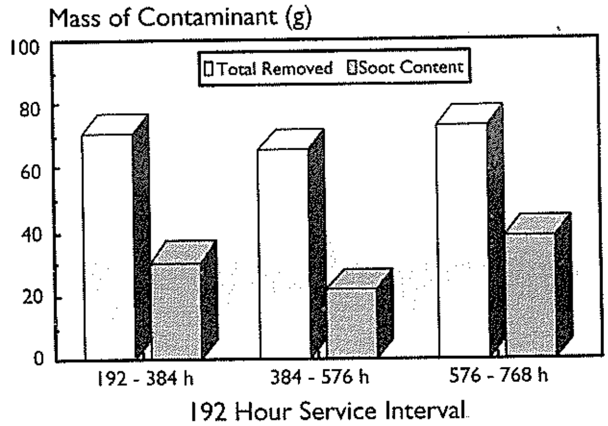

Fig 5.5 Total Mass & Soot Content of Contaminant Captured by Centrifuge

reduced by 20 - 30% with the introduction of a by-pass oil cleaning centrifuge.

With the exception of the first interval, the level of the main wear elements (eg Fe, Al, Cu, Pb, Si) within the oil of Engine 2 at the end of each 192 hour period was between 20% and 70% less than that observed in Engine 1 (Fig 5.6).

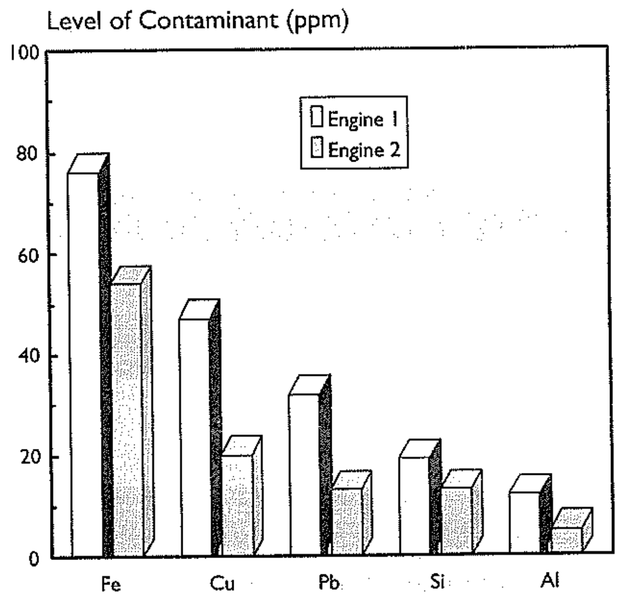

Fig 5.6 Level of Wear Elements Within Oil After Second 192 Hour Service Interval - Engines 1&2

8. OIL ANALYSIS RESULTS

8.1 Engines 1&2, 384 Hour Service Interval (768 - 1152 Hours)

Figs 5.7, 5.8, 5.9 and 5.10 show the level of the major wear elements detected within the oil of both engines throughout the service interval. On completion of the interval the oil in Engine 2, when compared to that in Engine 1, contained 33% less iron, 27% less lead, 31.3% less copper

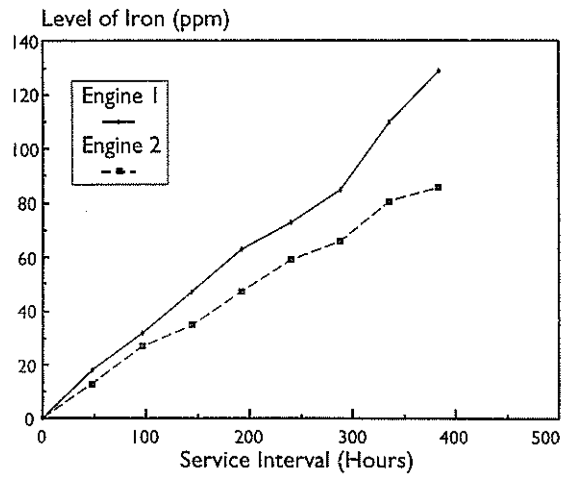

Fig 5.7 *Rate of Increase of Iron Contaminant (768-1152h) - Engines 1&2*

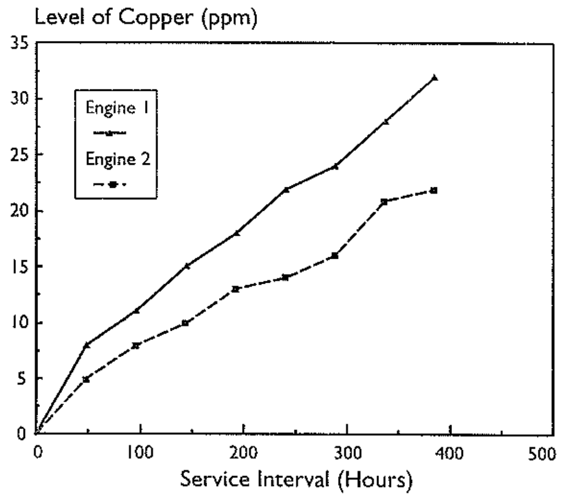

Fig 5.8 *Rate of Increase of Copper Contaminant (768-1152h) - Engines 1&2*

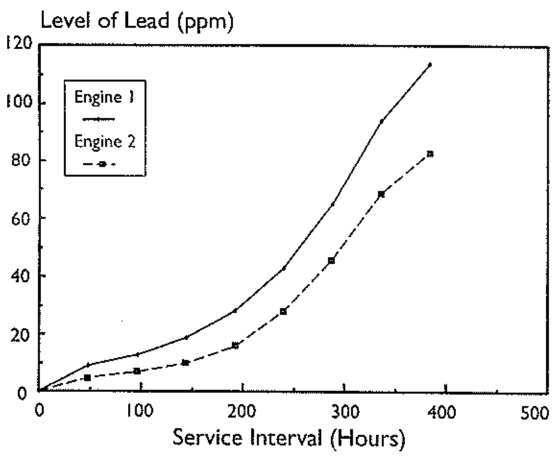

Fig 5.9 *Rate of Increase of Lead Contaminant (768-1152h) - Engines 1&2*

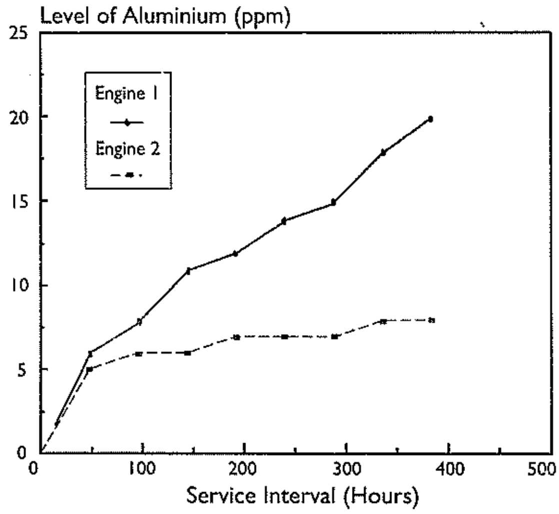

Fig 5.10 *Rate of Increase of Aluminium Contaminant (768-1152h) - Engines 1&2*

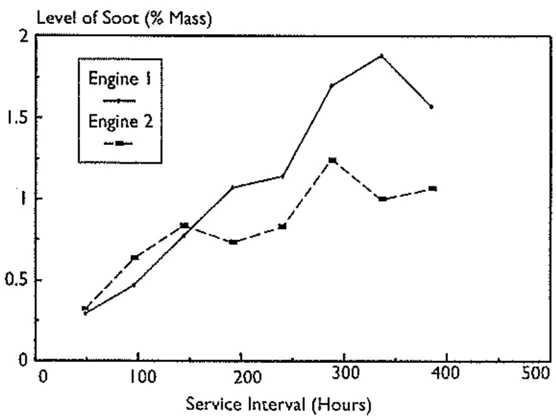

Fig 5.11 *LEM Results - Rate of Increase of Soot (768-1152h) - Engines 1&2*

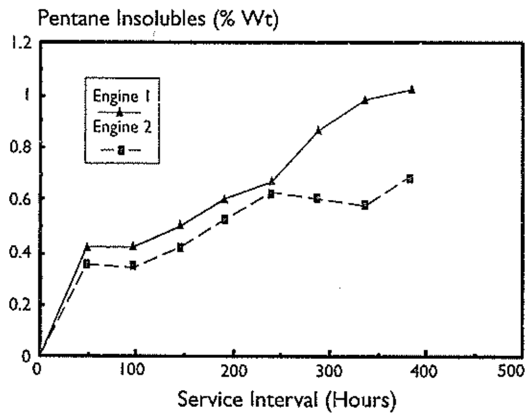

Fig 5.12 *Rate of Increase of Pentane Insolubles (768-1152h) - Engines 1&2*

and 60% less aluminium.

The LEM results depicting the rate of increase of soot contamination are shown in Fig 5.11. The percentage mass of soot in circulation at the end of the service interval was 1.56% (137.1 g) for Engine 1 and 1.06% (93.21 g) for Engine 2. It can therefore be concluded that the application of the centrifuge reduced the mass of soot in circulation within Engine 2 by approximately 43.89 g, or 32%.

The results displayed in Fig 5.12 show the rate of increase of Pentane insolubles (soot & traces of wear metals) of a size greater than 0.3 microns. On completion of the 384 hour interval Engine 2 had considerably less Pentane insolubles in circulation than Engine 1. The reduction measured was similar (31.4%) to that determined from the LEM results (32%).

Values obtained for viscosity, TBN, TAN, nitration, additive depletion and oxidation throughout the 384 hour interval were considered to be satisfactory. Fig 5.13 displays the results for the depletion rate of the oil dispersency additive package, and shows the depletion rate for the oil in Engine 1 to be greater than that in Engine 2. This characteristic was observed throughout the complete engine test programme.

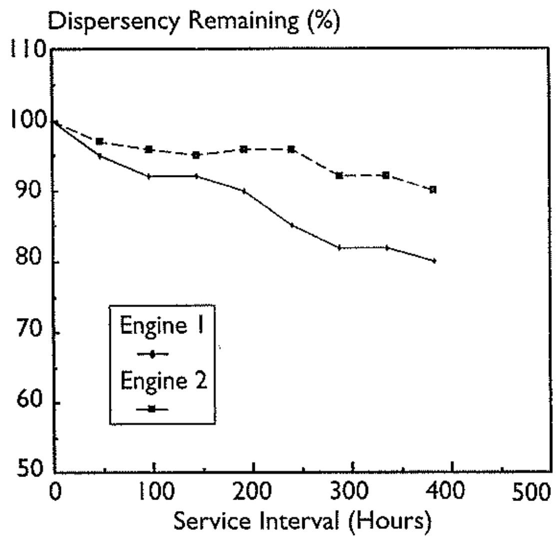

Fig 5.13 Depletion Rate of Oil Dispersency Package (768-1152h) - Engines 1&2

8.2 Engine 3, 0 - 384 Hour Service Interval

Figs 5.14 and 5.15 show the level of insolubles and soot generated throughout 384 hours. In order to provide a comparison, the results for Engines 1 & 2 during the first 192 hour service interval (Engine 2 without centrifuge) are also displayed.

It can be seen that the rate of increase of insolubles and soot in circulation within Engine 3, fitted with a by-pass centrifuge and full flow screen, was lower than that of the other two engines. After 192 hours reductions of 17.4 - 21.6% insolubles and 26.3 - 31.4% soot were measured.

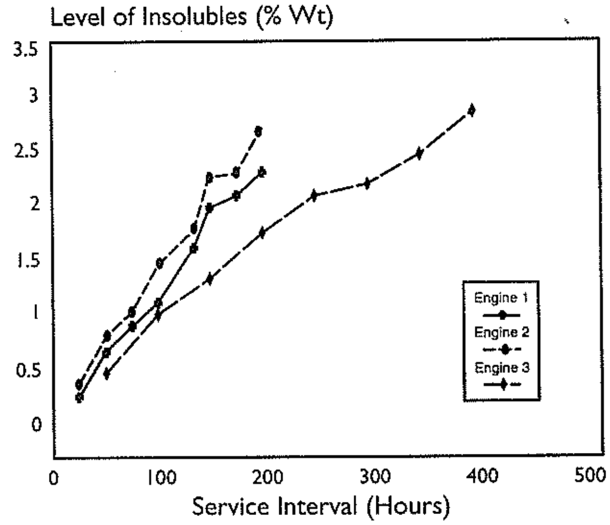

Fig 5.14 Rate of Increase of Total Solubles - Engine 3: 0-384h; Engines 1&2: 0-192h

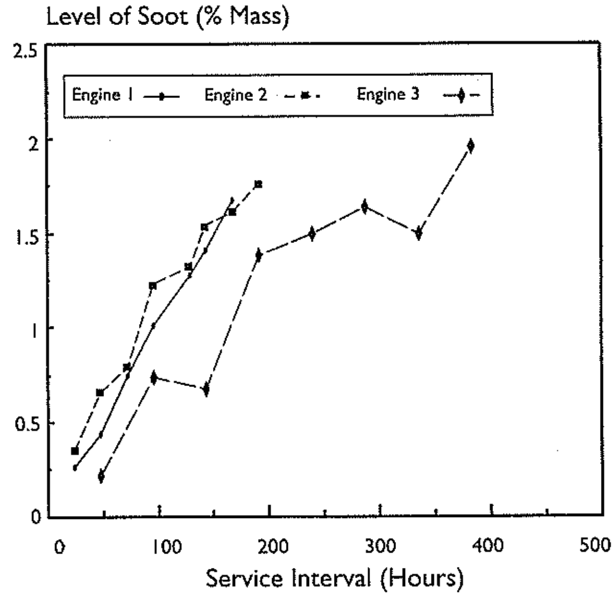

Fig 5.15 LEM Results - Rate of Increase of Soot - Engine 3: 0-384h; Engines 1&2: 0-192h

It should be restated that Engines 1 & 2 were flushed through after manufacture and had an oil change after a 15 hour run-in cycle, whereas Engine 3 retained the same oil from production to 384 hours. If operated without a centrifuge, it is reasonable to assume that the level of insolubles within Engine 3 would have been considerably higher than that measured for the other two engines. This assumption is confirmed by examination of the contaminant captured by the centrifuge during this test period (see Section 9).

Fig 5.16 displays the values obtained for Pentane insolubles throughout 384 hours, and includes the results

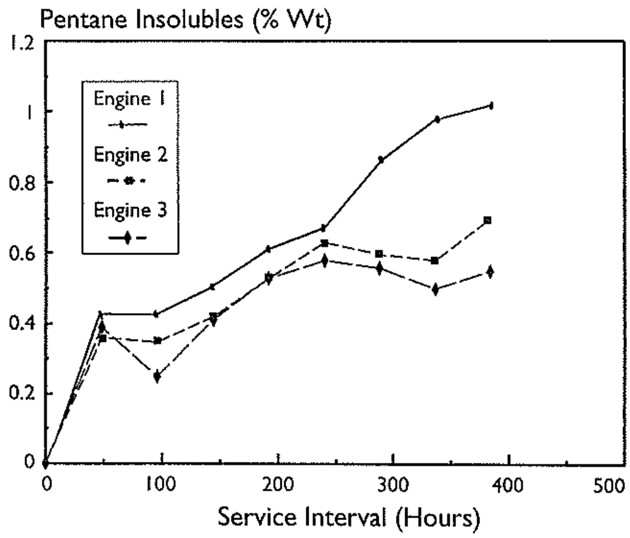

Fig 5.16 Rate of Increase of Pentane Insolubles - Engine 3: 0-384h; Engines 1&2: 768-1152h

from Engines 1 & 2 operating for the same interval (768 - 1152 hours). It should be noted that the centrifuge on Engine 2 was operational during this period of the test programme.

The application of the centrifuge to Engines 2 & 3 was clearly beneficial in reducing the rate of increase of Pentane insolubles; after 384 hours a reduction of 31.4 - 45% was measured.

It was interesting to note the similarity between the curves for Engines 2 & 3. This clearly demonstrates that the introduction of a 45 micron full flow screen in place of a 15 micron element filter made little difference to the end result. It can therefore be concluded that the majority of contaminant particles in circulation were less than 15 microns in size and were effectively controlled by the use of a by-pass centrifuge.

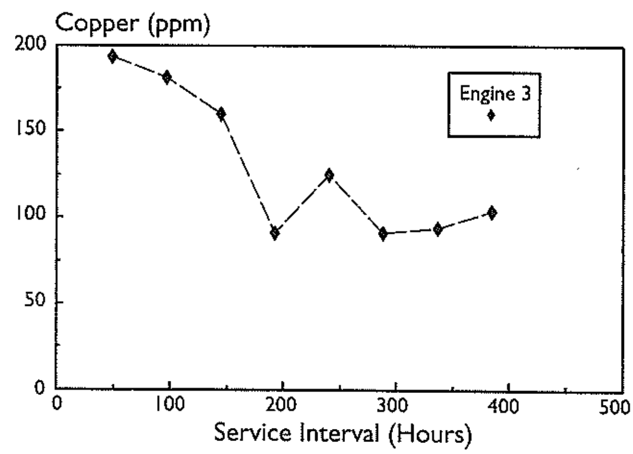

Fig 5.17 Level of Copper Contaminant Particles - Engine 3

The abrasive wear elements in circulation throughout the 384 hour period were maintained at an acceptable level. It can be seen from Fig 5.17 that the level of copper fell from around 200 ppm to 100 ppm in the first 200 hours of operation and was maintained at this level throughout the remaining 184 hours. Iron was the only wear element to show a noticeable increase (see Section 9).

9. ANALYSIS OF CENTRIFUGE CAPTURED CONTAMINANT

Samples of the sludge contained within the centrifuges fitted to Engines 2 and 3 were taken on completion of the 384 hour service interval. Measurement of Pentane insolubles, optical analysis by scanning electron microscope (SEM), X-ray diffraction and RDE spectroscopy were techniques used to determine the composition of each sample.

The total mass of contaminant captured over 384 hours was as follows:

Engine 2 (768 - 1172 h): 97g

Engine 3 (0 - 384 h): 135.6g

The composition of this contaminant was as shown in Table 5.3. Soot particles of a size greater than 0.3 microns accounted for 58.8% of the total contaminant removed from Engine 2 (57.04g) and 55.2% from Engine 3 (74.85g). Particles of a size less than 0.3 microns were also present within the contaminant removed, but the exact quantity could not be determined with the analysis technique adopted.

	OIL & SOOT <0.3 microns	SOOT & TRACES OF WEAR METALS >0.3 microns	SPENT ADDITIVE
Engine 2	42%	55.2%	2.8%
Engine 3	36%	58.8%	5.2%

Table 5.3 Composition of Contaminant Captured by Centrifuge

From the LEM analysis results for Engine 3 (Fig 5.15) it was determined that the soot in circulation after 384 hours was 172.34 g, ie 1.96% soot (from Fig 5.15) x 8793g (the total mass of oil in circulation). Without a centrifuge fitted it is reasonable to assume that this level would be in excess of 247.19g (ie 172.34 + 74.85g). Thus the operation of the centrifuge on Engine 3 reduced the level of soot loading within the oil by more than 30%.

Since Engine 3 was operated using the same oil from manufacture to 384 hours, it was expected that there would be a considerable increase in contaminant either within the oil or in the centrifuge. However, since the wear elements within the oil were maintained at an acceptable level throughout the service interval, it is clear that the centrifuge was efficient in removing this excess contaminant. This was confirmed by comparing the spectrographic analysis results obtained for the contaminant removed from Engines 2 and 3 (Fig 5.18).

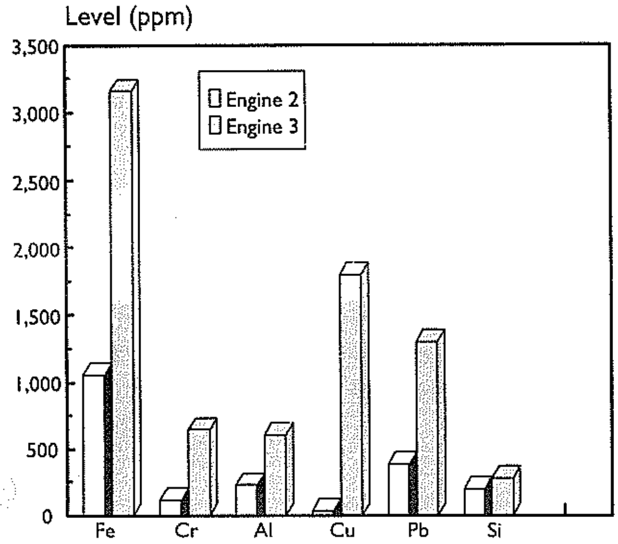

Fig 5.18 Spectrographic Analysis - Level of Wear Elements Captured by Centrifuge - Engine 2: 768-1152h.; Engine 3: 0-384h

The contaminant removed from Engine 3 contained considerably higher levels of wear metals than that captured from Engine 2 (eg 300% increase in iron).

Fig 5.19 shows the size distribution of metallic wear particles captured by the centrifuge. The results display the different sizes as a percentage of the total number of wear particles counted by a scanning electron microscope.

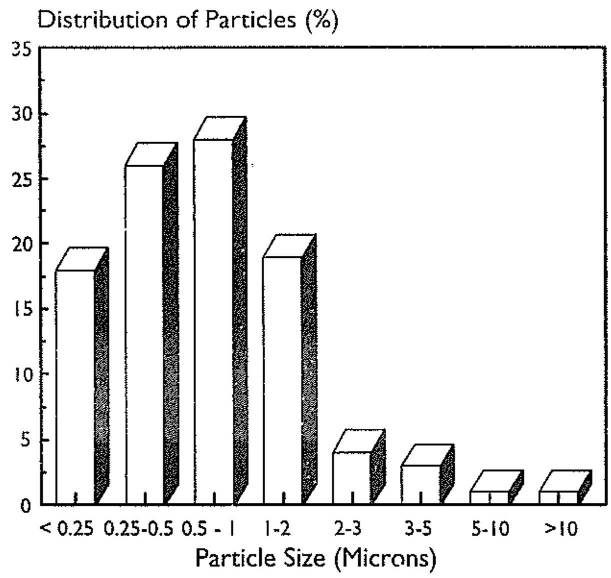

Fig 5.19 Particle Size Distribution in Contaminant Captured by Centrifuge

It can be seen that 91% of the metallic wear particles observed were less than 2 microns in size.

10. OPTICAL ANALYSIS OF FULL FLOW CLEANABLE SCREEN

On completion of 384 hours operation by Engine 3 the screen was washed and the particulate removed and filtered. The weight of particulates (metallic and non-metallic) was 0.394g.

Examination by SEM indicated that approximately 70% of the metallic particles in the sample were ferrous, a further 20% were copper based, 6% were aluminium and the remaining 4% were mainly lead.

11. CONCLUSIONS

The largest constituent of lubricating oil contaminant found within a diesel engine is soot. Over the years soot levels have increased with the need for lower oil consumptions, longer service intervals and the use of exhaust gas recirculation.

Throughout the test programme the oil in the engines fitted with a by-pass centrifuge contained, on average, 30% less soot than that in the engine operated with standard filtration. Analysis of the contaminant captured by the centrifuge has shown that more than 56% of its composition can be attributed to engine clogging soot.

When operated over a service interval of 384 hours, the level of soot and traces of wear metals of a size greater than 0.3 microns (Pentane Insolubles) in the oil was seen to be reduced by 31.7% with the introduction of a by-pass centrifuge.

The rate of depletion of the oil dispersency package was lower in the engines fitted with the centrifuge. Further testing is required to investigate this result fully, although the result is reasonable when considering the reduction in contaminant loading within the oil achieved through the operation of the centrifuge.

The application of an oil cleaning centrifuge greatly reduced the level of wear elements in circulation. Through analysis of the contaminant removed by the centrifuge it was shown that the majority of wear elements present were of a size less than 2 microns. Particles in this size range would pass through the standard full flow filter, but are of similar magnitude to the thickness of the oil films protecting the critical engine components. If not removed such particles cause wear and reduce engine durability.

The combination of a 45 micron metal full flow screen with a by-pass oil cleaning centrifuge was shown to be beneficial when compared to standard full flow filtration. Reductions in soot loading, total insolubles and Pentane insolubles were of similar magnitude to those achieved by the centrifuge operating in combination with the standard 15 micron full flow filter. It can therefore be stated that the operation of the centrifuge was the main contributor in maintaining oil condition, whereas the full flow filtration device acted as protection against the circulation of large debris likely to cause catastrophic failure.

Examination of the rotor contents after 384 hours of engine testing indicated that 135.6g of dirt was collected. Comparing this quantity with the mass holding capacity of the GF016 rotor (200g) suggests that the rotor would be able to operate effectively up to 560 hours, or the equivalent of 60,000 on-road kilometers. An oil filtration system able to maintain oil cleanlines for this duration of on-road activity provides the opportunity for time based (possible annual) oil drains rather than activity based service intervals.

It can be concluded that the application of a by-pass centrifuge will assist engine designers in meeting future requirements for lower oil consumption, extended service intervals, emission control and increased durability. In addition, the combination of a centrifuge with a full flow cleanable screen is an environmentally and technically superior solution to that of existing disposable element filtration.

ACKNOWLEDGMENTS

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