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Oil Quality in Diesel Engines With On Line Oil Cleaning Using a Heated Lubricating Oil Recycler

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SYNOPSIS

A method of cleaning the oil on line was investigated using a bypass fine particulate filter followed by an infra red heater to remove water and light diesel fractions in the oil. This was tested on a range of on road vehicles and a Ford 1.8 litre IDI passenger car engine on a test bed. Comparison was made with the oil quality on the same vehicles and engines without the on-line recycler. Test times were from 200 to 1500 hours of oil ageing and some of the tests showed that the oil quality was still good after 4 times the normal oil life. The results showed that the on line oil recycler cleaning system reduced the rate of fall of the TBN and rate of increase of the TAN. There was a very significant reduction in the soot in oil and the fuel dilution. There was also a consistent reduction in all the wear metals apart from copper and a decrease in the rate of reduction of oil additives. There was also measured on the Ford IDI engine a 5% reduced fuel consumption. Many of these effects were attributed to an influence of the cleaner oil on reduced engine deposits.

INTRODUCTION

Modern low emission engines have a low oil consumption in order to reduce the unburnt lube oil fraction of the particulate emissions. This results in a lower rate of topping up of the oil and a possible greater rate of deterioration of the oil. In older engines the higher soot emissions result in higher soot in the oil. For both types of engines there is concern over oil quality (1-21) and the contribution of the oil to engine out emissions.

Diesel particulates are composed of carbon, ash, sulphates and a volatile fraction which is mainly vaporised lubricating oil. Lubricating oil also contributes to the carbon emissions through the combustion of lube oil in the cylinder. Both of these sources of particulates are influenced by the physical properties of the lubricating oil, viscosity and volatility, and these properties vary with the age of the lubricating oil. This is because of the accumulation of soot in the oil as well as water and unburnt fuel.

Future diesel emission legislation requires the emissions to be maintained over long distances of the order of 100,000 km and this combined with the low lubricating oil consumption required for low diesel particulate emissions can result in the lubricating oil age influencing the deterioration of emissions with distance. This work is concerned with a technique to keep oil clean, extend its life and reduce the increase in emission that occurs with aged oil.

At the same time as these emissions regulations have come into force, the trends in the diesel design towards higher ring zone temperature and pressure, piston redesign for higher top rings and higher piston temperatures, and extended service interval requirements are making it increasingly difficult to control deposit formation in the engine with traditional oil additive technology (22). Diesel deposits can be classified into two types: ring zone and piston skirt deposits (varnish). The higher ring zone temperatures (325-360C) promote thermal degradation of the lubricating oil and unburned/oxidized fuel components producing a ‘carbon’ deposit. At relatively low piston skirt temperatures (200-260C) a varnish type deposit predominates (22).

The primary source of piston deposits is the lubricant and lubricant oxidation is the primary cause of deposit formation (22). Diesel engine deposits also increase with the oil consumption (23), the piston temperatures (24) and the oil soot content (24). Engine deposits are a source of unburnt hydrocarbons through absorption and they also act as a cylinder insulation which increases NOx emissions because of the higher cylinder temperatures (25).

Oil viscosity also increases with the oil soot content (16, 26-28) which typically accumulates at a rate of 4% of the engine particulate mass emissions (14, 29). This results in the oil consumption increasing with the increase in viscosity (30) and also the fuel consumption increasing due to the increase in viscosity. Consequently, on line oil cleaning can result in reduced soot in the oil and in reduced fuel and water oil dilution and both of these effects can result in reduced engine deposits and a reduction in oil consumption. The reduced engine deposits can also result in reduced engine friction and hence reduced fuel consumption. Thus, improved oil quality can have additional benefits apart from the extended oil life.

THE ON LINE OIL RECYCLER

A method of continually cleaning the engine oil on line was investigated that was based on the combined effects of a bypass fine oil particulate filter with a 5-6 micron filter element followed by an infra-red dome heater which heated the oil to 135C as it flowed over a conical cascade into a drain return to the oil sump. This cascade also acted as an oil degassing element and this action can reduce erosion wear in bearings (21).

The gases evolved were vented through the centre of the dome heater to the engine inlet air. These gases were collected in an ice trap and analysed and it is shown below that they were mainly water with about 3% hydrocarbons. The tests were carried out on a stop start cycle with a fresh start approximately every two hours. This gives a large number of cold starts which increases the water in oil and maximises the length of time the oil in the sump is well below the boiling point of water. Water contamination of oil at a level in excess of 0.1% is one of the key reasons for changing the lube oil. A higher heater temperature would be required to distil more of diesel fuel dilution from the oil and this is being investigated at present. The use of by pass filters is common in some large diesel engines, but is not usual in smaller engines of 6 litres or less.

The bypass filter flow rate was controlled by a small flow control orifice and the pressure loss across this was much larger than that across the filter. This was because the bypass flow rate was set to suit the infra-red heater capacity to heat the oil. If the flow rate was too high the temperature rise would be well below the heater temperature. The infra-red heater was controlled by an on-off temperature controller which resulted in a near sinusoidal time variation of the temperature with a peak temperature substantially higher than the mean. This could result in the effective temperature of the heater, in terms of the distillation range of fuel in oil components that were removed, being higher that the mean temperature of the heater and more closely associated with the peak temperature, which was about 180C.

The flow control orifice also resulted in a filter flow that did not vary as the filter became loaded with particulates. The filter flow capacity was of the order of 50 times the actual flow and typically, even with a loaded filter, the pressure loss was below 10% at the filter and more than 90% at the control orifice. For a clean filter the pressure loss was about 98% at the control orifice.

The filter element could be altered to achieve a greater fineness without affecting the bypass flow rate, as the increase in the filter pressure loss due to the finer filtration elements would still not be a major factor in the overall recycler pressure loss. Work is in progress to investigate whether the performance of the oil recycler system is improved by using filters of the order of 1 micron, as advocated by others (5, 15, 31- 33). However, the choice in the present work of 5-6 micron particle size filters was based on advice from hydraulic oil filter manufacturers that oil additives could be filtered out if the filter size was too fine and this may occur with 1 micron filters.

BYPASS FILTRATION

Bypass filters have two basic features: a high filtration efficiency and a high particulate storage capacity (31). They reduce the fine particulate matter in the oil leaving the main filter to remove the larger particulates. Stenhouer (32) showed that bypass filters removed organic material, sludge, varnish, resin, soot and unburnt fuel. His work showed that over 80% of the contaminant removed by the bypass filter was organic. Bypass filters can remove the small pro-wear contaminant particles thus extending engine component life (33). The benefit of bypass filter was then reduced wear and reduced in cylinder deposits. It is possible to arrange a combination filter whereby in one housing a main and bypass filter are arranged (31) with the flow between the two splitting according to their flow resistances.

CENTRIFUGAL FILTER

Although a filter based bypass filter was used in the present work, centrifugal bypass filters are also quite common (33). These are of two types: powered and self powered and the latter are more common in automotive applications. A self powered centrifugal oil cleaner uses the dirty oil pressure to drive the cleaning rotor using centrifugal separation of the high density particles from the lower density oil. These contaminants collect as a hard cake on the inside of the rotor which can then either be cleaned off or disposed of as a unit (33). Centrifugal filters have an effective particle size removal below 1 micron and have a filtration efficiency that does not deteriorate with time (33). They are , however, generally more expensive initially than filter based bypass filters. One assessment of bypass filters (34) has determined the average size rating (50% removal) of a centrifugal filter as 6-10 microns and hydraulic oil filters as 2 micron. They also estimated that it would take 30 bypass filter changes before the cost of bypass filtration exceeded that of a centrifugal filter. This could be 10 years of normal use. Hydraulic quality bypass filters were used in the present work with an average size rating of 5-6 microns.

BYPASS FILTER AND HEATER - OIL RECYCLER

The combination of a bypass filter with an oil heater was first investigated by York (5) and further developed by Lefebvre (15), they used a one micron bypass oil filter with a 95C oil heater. York (5) claimed that this system significantly reduced metal wear and took 10,000 miles to clean an engine of already dirty oil and once cleared the oil remained clean with an indefinite life. However, no oil analysis results were presented.

Fuel dilution and acid pitting were significantly reduced using this combined bypass filter and oil heater. This is difficult to understand as diesel oil has no components that distil at 95C and even water would not be removed at this temperature. Oil consumption was also reduced and one example quoted was in excess of an 80% reduction in the oil consumed in a year. Lefebvre (15) reported the results of a commercial development of the system introduced by York and confirmed in fleet trials the reduction in wear metals and also showed that the action of the heater was to reduce the water in oil and to reduce diesel fuel dilution (15), but quantitative oil analysis results were not presented.

The present work investigates an improved design of the same basic principles and uses a different construction and does not have direct contact of the oil with the heater surface as in the work of York (5) and Lefebvre (15). Also commercial hydraulic oil quality bypass filters were used not the specially manufactured filters used by York and Lefebvre. The size of the present units for the same application are also substantially smaller and lighter than those used by Lefebvre and are more easily package into existing diesel engine installations.

EXPERIMENTAL TECHNIQUES

The experimental evaluation of the bypass heated oil recycler was undertaken in two parts: a long duration test on a Ford 1.8 litre IDI engine in the laboratory and a series of fleet trials with regular oil analysis. In both cases the engine oils were analysed with and without the Recycler fitted to the same vehicle. The recycler oil heater was set at 135C for these tests and a hydraulic quality bypass filter was used with a 5-6 micron mean particle size removal. The gases vented out of the top of the heater were collected in an ice trap and analysed by capillary GC after separation of the water.

THE FORD 1.8 LITRE NA IDI ENGINE TESTS – This engine was water cooled with a compression ratio of 21.5/1 and had external EGR for NOx control. The engine was manufactured in 1992. These tests were carried out at an engine speed of 2500 rpm and 47 Nm load and 12.3 kW power output and this is typical of the low power output in the ECE Urban drive cycle. At this test condition the engine uncooled EGR level was 15%. The test were all carried out at one engine test conditions so that a mass balance between the engine particulate emissions and particulate entering the lube oil could be carried out.

The engine was tested on a stop start cycle with each running period being about two to three hours and with one or two running periods per day. The tests were carried out over a period of about a year with engine out of use periods that reflect actual use. This procedure was used to age the oil as it is more representative of real vehicle use compared with continuous long duration testing of the oil.

The cold start is a major factor in oil deterioration and engine wear, as this is the time for maximum fuel dilution and water from the blowby gases as well as maximum wear in the engine. The particulate emissions are also higher when the engine is cold and hence particulate emissions and particulates entering the lube oil are higher under repeated cold start operation.

The fresh oil was filled to the top of the level indicator and the present tests were carried out until the oil consumption reduced the oil to the bottom of the minimum level indicator and this took 220 hours of testing with the recycler fitted. There was no top up oil added during this test period. The reference tests without the recycler were only carried out for 100 hours and these were the first tests to be carried out.

Fig. 1 shows the number of engine starts as a function of the oil age for the tests with and without the recycler. The average cycle time was 2.5 hours. The recycler oil flow rate was such that the total sump oil volume passed through the bypass filter about 5 times per hour. The total number of times that the oil sump volume was passed through the recycler is shown in Fig. 2 as a function of the oil age. Well over 1000 oil sump cycles through the bypass filter took place during the 220 hours oil ageing test or approximately 4 sump volumes per hour.

THE FLEET TRIALS – The fleet trials were carried out with normal road operation of the vehicles and there was no control over the journeys. The oil condition without the recycler was generally only available by analysing a sample of the oil at the normal oil change. The heated oil recycler was then fitted and the engine oil changed. Four vehicles were investigated: Cummins C6 and L10 engines in bus trials, a Gardner 6LXB bus engine and an old Austin Taxi Cab test. There was no control or record of the oil topping up during these trials and the results discussed below clearly show that there must have been topping up of the oil when the recycler was fitted during a test that lasted 17000 miles.

THE OIL ANALYSIS – Oil was sampled periodically from the dip stick using a vacuum pump and syringe with the sample taken through a flexible tubing located just below the oil surface in the sump and collected in a small glass bottle. The volume sampled was noted and taken into account when the oil consumption by the engine was determined by draining the sump at the end of the test.

The oil sample was analysed for total base number (TBN) and total acid number (TAN), viscosity, soot by infra red and by thermal gravimetric analysis, wear and additive metals and additive depletion using FTIR. The oil used was SAE 15W/40 and had a viscosity index for the fresh oil of 136 and a viscosity at 100C of 14.4 mm2/s and at 40C 108 mm2/s. The main oil analysis was carried out to current standard methodology at Swansea Tribology Services Ltd. and the TGA and FTIR work was carried out at Leeds University.

The thermal gravimetric analysis (TGA) technique was used to determine fuel dilution of the oil, carbon and ash content. The method used a small sample size of approximately 50 mg that was placed in a small bowl hanging from a microbalance. This was then heated in an oven in a flow of nitrogen and the weight loss as a function of temperature was determined up to 700C temperature. The nitrogen was then switched to air and the heater increased to give 710C and any carbon in the oil was burnt away and the remaining weight was the ash in the oil.

The weight loss in nitrogen was calibrated to enable the fuel dilution to be determined. This is done on an oil volatility basis and the method cannot distinguish between oil degradation to give volatile low molecular weight components and fuel dilution. The calibration was undertaken with diesel/lube oil mixtures in the 0.5-5% fuel range and it was found that a temperature of 290C for the oil and fuel used in this work enabled the fuel dilution to be determined as the weight loss up to 290C. In addition to this the temperature at which the first 1% weight loss occurred was also determined, as a decrease in this temperature is also indicative of fuel dilution. Full details of these techniques are given in Refs. 6, 7, 9, 10, 14 and 20.

RESULTS

THE OIL RECYCLER VENT GASES – The gases evolved from the heated recycler vent in the Ford 1.8 litre IDI tests were collected in an ice bath and analysed. Fig.3 shows the water condensed from the vent as a percentage of the oil in the sump. This would have been the lube oil water content if the heated recycler had not been fitted. Throughout the tests the oil analysis showed the water content to be below 0.1%. One reason for rejecting used lubricating oil is a water content above 0.2% of the oil and the recycler helps to prevent this level of water in oil from occurring.

There were some hydrocarbons also released and a GC of these is shown in Fig. 4. The large broad peak at 50 minutes into the GC trace was lubricating oil condensed vapours. The other peaks were not similar to diesel components but were in the distillation range of diesel. After separation of the water the remaining hydrocarbons in the condensed extract were very low in mass and the total vented hydrocarbons that were collected in the first 150 hours was 113 mg, roughly 3% of the water collected. This represents a very low fuel dilution of the oil at 0.003% of the oil and higher heater temperatures would be required if fuel dilution of the oil was a problem.

FUEL DILUTION OF THE OIL – It was found that the heated recycler did have a measurable influence of the initial distillation temperature of the oil using TGA analysis. This is shown in Fig. 5 for the Ford IDI engine, which shows that with the recycler fitted the temperature for the first initial weight loss of the oil (1% distillation fraction) was roughly constant with time but decreased without the recycler fitted. A decrease in the first distillation temperature is a characteristic of fuel dilution or of oil degradation that results in lower boiling fractions in the oil. These results show that even at 135C the oil heater was influencing the initial distillation range of the oil and hence possibly the amount of fuel dilution. Pyrolysis GC analysis of the used lubricating oil at 0 and 220 hours is shown in Fig.6 for the oil with the recycler fitted. There is very little evidence of diesel fuel dilution in these results. N-alkanes with carbon numbers of C20, C21 and C22 can be seen in the lower boiling fractions of the oil. Previous work by Andrews et al (14) showed that fuel dilution of the oil was easily seen in Pyrolysis GC analysis of the oil after 70 hours. Thus, the absence of a major increase in the fuel component peaks in the 220 hour oil indicates a control of fuel dilution by the recycler.

The GC traces also show that the aged lubricating oil had a broader GC trace after 220 hours use, indicating the formation of a wider range of compounds as the oil ages. The main increase in the width of the CG trace is towards longer GC retention times which indicate higher boiling fractions and larger molecular weight compounds. This indicates the formation of heavier oil fractions, which is a sign of oil deterioration.

The fuel dilution, determined using the TGA technique described above, is shown in Fig, 7 as a function of the oil age both with and without the recycler fitted. There is a clear advantage of the recycler, with no fuel dilution detectable until after 130 hours, compared with 0.8% after 50 hours without the recycler. This engine has good control of fuel dilution of the oil. In previous work (14) using an older Peter AA1 IDI engine the oil fuel dilution was 4% after 50 hours or five times the rate on the more modern Ford 1.8 litre IDI engine.

FIG.1 THE ENGINE START TIMES VS OIL AGE

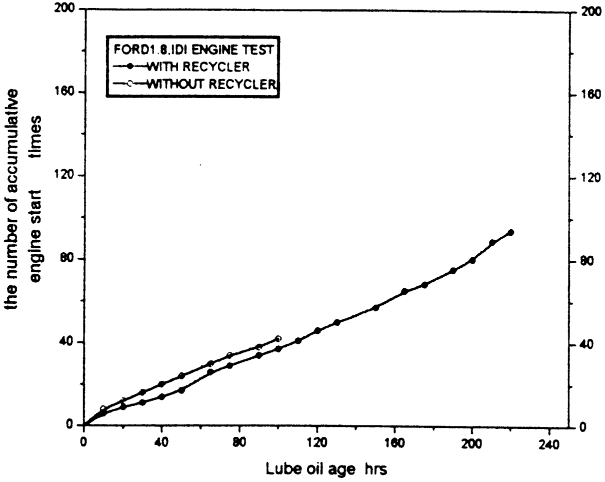


FIG.3 CONDENSED WATER BY THE RECYCLER ON FORD1.8 IDI ENGINE TEST

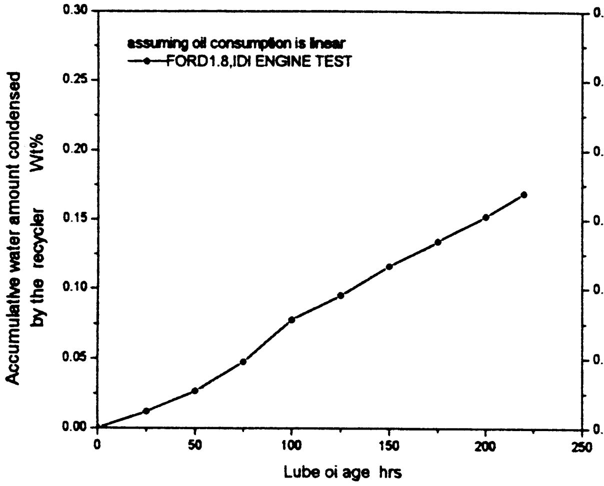


FIG.5 INITIAL EVAPORATING TEMP. BY TGA

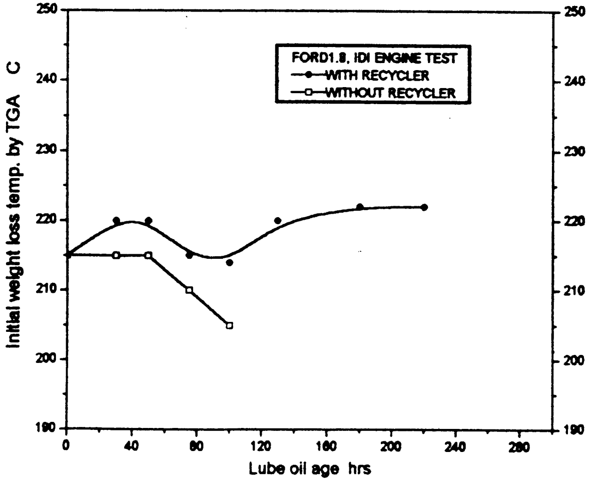


FIG.2 TIMES OF OIL RECYCLED VS OIL AGE

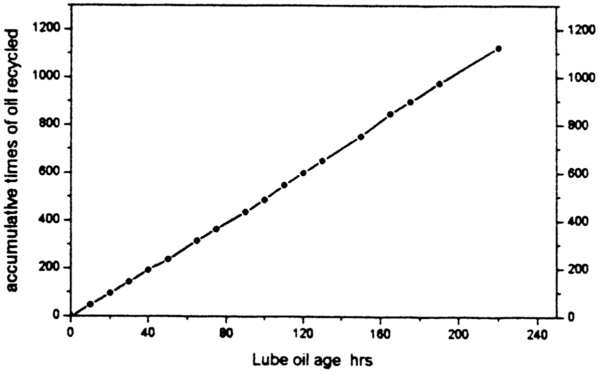


FIG4. GC ANALYSIS OF CONDENSATE FROM OIL RECYCLER HEATER VENT

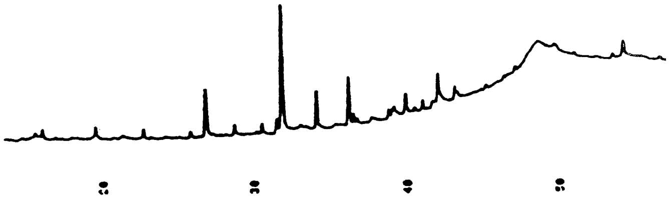
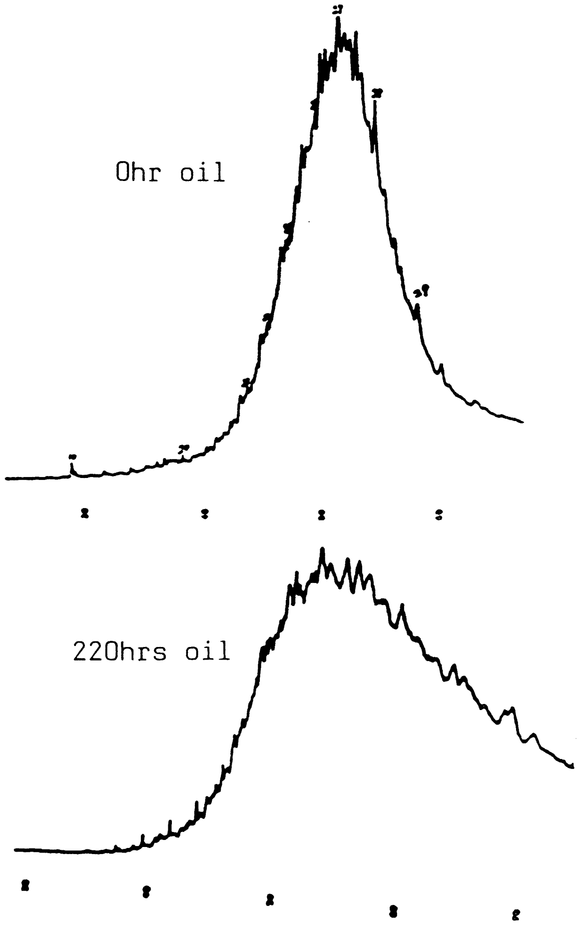


FIG.6 GC OF THE FRESH AND 220HRS OILS FROM FORD1.8 IDI ENGINE TEST



Thus in spite of the relatively low set point temperature on the recycler infra-red heater of 135C, there was a much stronger influence on the oil fuel dilution than would be expected. This could have been due to the on-off two step temperature control with the effect of the heater on the oil being controlled by the peak temperature in the cycle of about 180C rather than the mean temperature. Further work is in progress to investigate the influence of the heater temperature on the control of fuel dilution of the oil.

OIL VISCOSITY – The influence of oil fuel dilution is to decrease the oil viscosity, whereas the influence of soot accumulation in the oil is the increase the viscosity (8, 14, 16, 35). This can result in the oil viscosity as a function of the oil age first decreasing and then increasing with time. This can be seen in Fig.8 for the Ford IDI engine without the recycler. With the recycler the control of the fuel dilution eliminated the decrease in viscosity due to fuel dilution and the control of the soot in the oil, discussed below, resulted in a near constant oil viscosity for the first 220 hours. There was an initial decrease in the viscosity and this was associated with the burn off of the initial fresh oil volatile fraction. This also resulted in a large decrease in the particulate lubricating oil fraction, but this emissions data will be reported separately.

Figure 8 also shows the trials of the recycler on the Austin taxi, which shows that the recycler controlled the increase in the viscosity that occurred without the recycler. The viscosity with the recycler was almost constant with time for the 240 hours of this trial.

The results from the bus trials with the Cummins C6 engine are shown in Fig.9. This was the longest trial in this work and Fig. 9 shows that after 1700 hours the oil viscosity with the recycler fitted was below that without the recycler at the normal oil change of 400 hours. With the recycler the viscosity first decreased to a minimum at 400 hours and then slowly increased again as the soot started to build up in the oil. These results show that with the recycler system fitted the oil life was at least 4 times longer than without the recycler. The results for other oil quality parameters also support this large increase in the oil life in these trials.

Figure 10 shows the normalised oil viscosity results plotted as a function of time for the Ford IDI, the Austin taxi and Cummins C6 bus trials for the first 450 hours and all without a recycler fitted. These are compared with the results for a Caterpillar engine in Ref. 16 with three different oils. These results show a 5% decrease in viscosity after 50 hours compared with a 10% decrease at the same oil age in the Ford engine. The increase in viscosity with soot loading was steeper for the Caterpillar engine (16) than for the present Cummins C6 results but similar to the Austin taxi results. This comparison indicates that the baseline viscosity results in this work are comparable with other aged oil tests and hence the engines used in the present tests of the oil recycler were not unusual in their oil ageing behaviour.

FUEL CONSUMPTION VARIATION WITH OIL AGE – The fuel consumption was determined at each oil age test period with and without the recycler fitted for the steady state condition of 2500 rpm and 12.3 kW power output. The fuel consumption results are shown in Fig. 11 and have been normalised to the value with clean fresh oil with and without the recycler fitted. The results show that without the recycler the fuel consumption increased by about 5% over 100 hours of oil ageing. This increase could not be due to viscosity increases, which is the normal cause of an increase in fuel consumption with oil age, as Fig. 8 shows that the viscosity decreased over the first 50 hours which could be attributed to the decomposition of viscosity index improver additive in the fresh oil. The formation of in cylinder deposits more rapidly from fresh oil could be one explanation of these results.

The fuel economy with the oil recycler fitted was very similar for the first 20 hours and then decreased progressively to a minimum after 120 hours after which there was a gradual deterioration. These effects were not mirrored by a corresponding change in the oil viscosity, which Fig. 8 shows initially decreased and then remained approximately constant. The increase in oil consumption after 120 hours could be due to soot accumulation in the oil, as discussed below, although this normally affects the fuel economy through an increase in the oil viscosity. It is therefore concluded that most of the small effects in Fig. 11 were due to the action of the recycler in minimising the formation of in cylinder deposits and assisting in the reduction of existing deposits through the supply of cleaner oil.

After 100 hours the fuel economy was 8% lower with the recycler fitted than without the recycler for the same oil age and engine use over the ageing period. However, between 70 and 90 hours the economy benefit was approximately 5%. These results indicate that an additional benefit of the use of the on line oil cleaning using a bypass recycler could be a small reduction in the fuel consumption of the order of 5%. This was considered to be mainly due to the action of cleaner oil in reducing deposit formation and hence in reducing engine friction.

SOOT IN THE OIL – The main action of the bypass filter part of the recycler was to reduce the soot in the oil and the wear metals. The soot in oil reduction was determined using infra red absorption for all the engine tests and by TGA for the Ford 1.8 litre IDI tests. The Ford and the Austin Taxi results are shown in Fig. 12 using the infra red absorption measurement of soot in the oil.

The reduction in soot in the oil for the taxi tests was substantial using the recycler, but at 100 hours was only slightly lower than without the recycler for the Ford engine. However, the TGA tests for the Ford engine showed a very significant influence of the recycler on reducing the carbon in oil. This was reduced from 0.9% to 0.3% at 100 hours and even after 220 hours was only 0.5%. Oil would normally be recommended for change when soot in oil was greater than 1-2%.

Fig.7 FUEL DILUTION OF THE OILS(BY TGA)

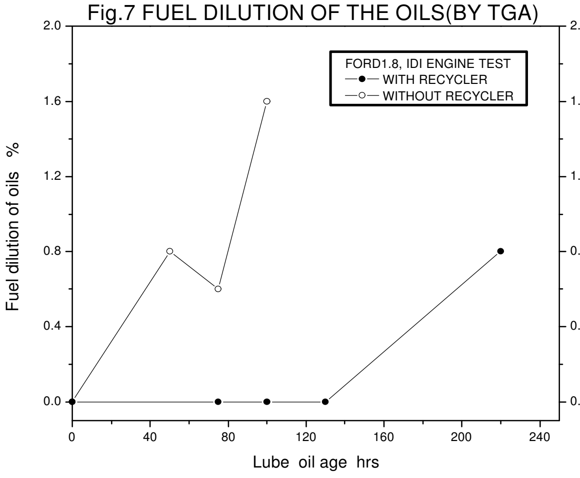


FIG.8 OIL'S VISCOSITY CHANGE FROM TAXI AND FORD1.8 IDI TESTS

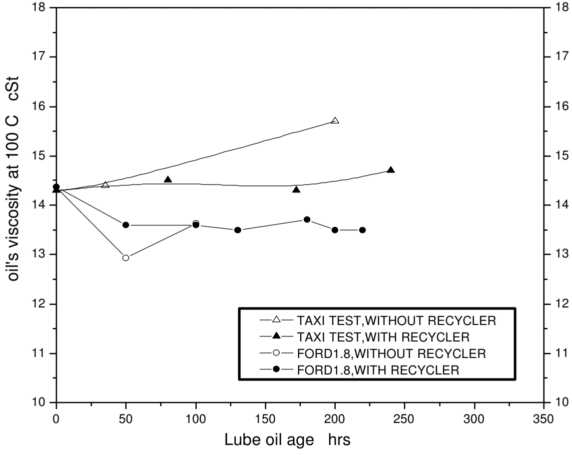


FIG.9 OIL'S VISCOSITY CHANGE COMPARISON FROM THE BUS TRIAL

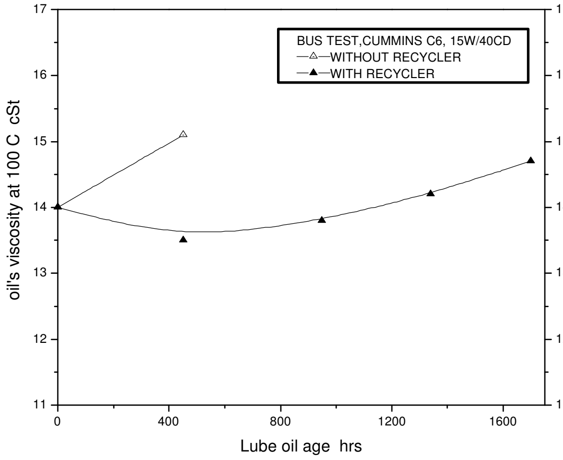


FIG.10 OIL'S VISCOSITY CHANGE RATE ON SOME ENGINE TESTS

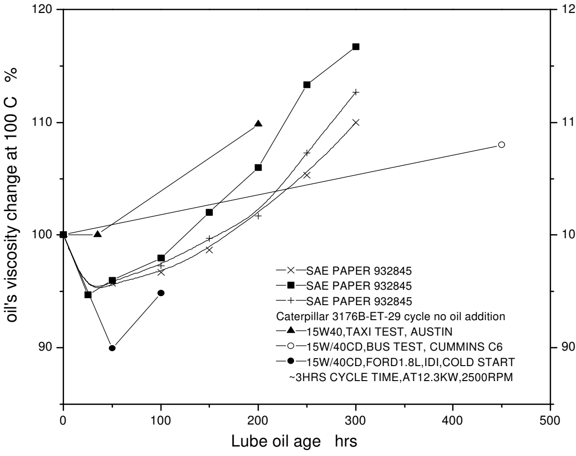


FIG.11 FUEL CONSUMPTION RATE BY %

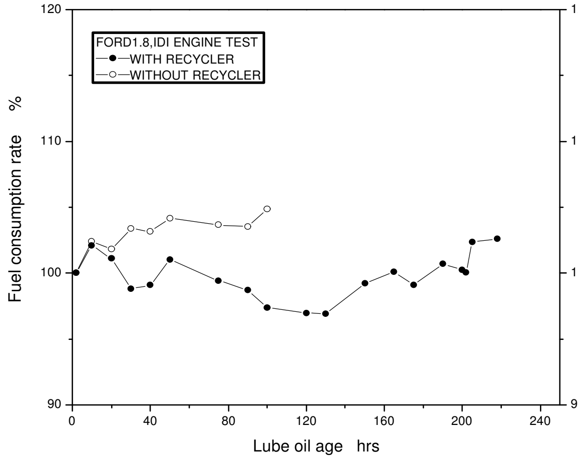
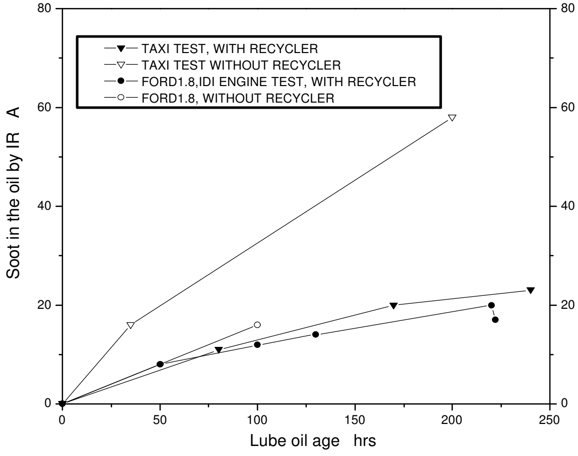


FIG.12 SOOT CONTENT OF OILS ON TAXI AND FORD1.8 ENGINE TESTS



The Cummins C6 bus test results are shown in Fig.14 and again there was a major reduction in the soot in the oil by the infra-red absorption technique. At the normal oil change period of 400 hours this had been reduced by a factor of four with the recycler and even after 1700 hours the soot content with the recycler was below that without the recycler at 400 hours. These results show that the bypass filter, which forms part of the dual action of the recycler, is effective in reducing soot in the oil at the 5-6 micron filter size that was used. Work is in progress to examine whether there are further benefits from using finer bypass filtration.

OIL ADDITIVE DEPLETION – Zinc dialkyldithiophosphate (ZDDP) is a dual purpose lube oil additive with anti-oxidant and anti-wear properties. ZDDP decomposes during running of the engine and forms complexes with metal surfaces and the lubricating properties of the used oil are maintained by these complexes. Chemical reaction takes place between the metal surface and the lubricant additive ZDDP. The products of this type of reaction are usually low shearing strength and high melting point compounds such as sulphides and phosphides and these behave as solid lubricants at high loads and prevent metal to metal contact (36). Thus ZDDP is designed to be consumed to some extent before oxidation and wear starts, or in other words before the formation of carboxylic acids.

ZDDP additives do not work well under cold start conditions, which is one reason for the use of stop/start repeated cold start ageing of the oil used in the present work. It is one reason why engine wear is greater under uses where there are many engine starts a day. Valve wear in engines has been shown to be increased due to diesel soot or carbon contamination of the crankcase oil, in which the antiwear agent is absorbed and thus the antiwear surface coating is reduced (38). This is likely to be the route by which the oil recycler produces a reduced ZDDP loss from the oil, as detailed below, by reducing the oil soot content and hence the removal of ZDDP by absorption onto the soot.

ZDDP was determined from FTIR spectra of the used oil. ZDDP appears around 973 cm -1 very strongly and also at 670 cm -1 as a stretch absorption band. Previously, Wooton et al. (37) have shown that ZDDP is depleted quite rapidly with two thirds disappearing in the first 70 hours and 90% disappearing after 200 hours.

The ZDDP present results in a modern light duty passenger car engine are shown in Fig.15. For the engine with no recycler fitted the ZDDP depletion was 31% after 100 hours, substantially slower then in the work of Wooton et al. With the recycler fitted Fig. 15 shows that the ZDDP depletion was reduced to 22% at 100 hours and was only 58% at 220 hours, which is a much slower rate of depletion than in the work of Wooton et al. (37). The oil recycler made a 30% reduction in the rate of depletion of ZDDP compared with the base engine results at 100 hours.

The recycler results extrapolated to zero ZDDP indicates that the oil life in terms of ZDDP remaining was at least 400 hours. However, top up of the oil and ZDDP replenishment was required at 220 hours. The reason for the reduced depletion of ZDDP was considered to be due to the reduced soot content and the associated absorption of ZDDP on the soot. This left more ZDDP for wear protection and was part of the reason for the reduced wear metals in the oil, as shown below.

OIL TBN AND TAN – The total base number (TBN) is a measure of the reserves of alkalinity present in the oil. A value below 5 is generally regarded as undesirable (38). The total acid number (TAN) is a measure of the total amount of both weak and strong organic acidity present in the oil. Lube oil oxidation can result into conversion into acids which attack and corrode metals. Lube oils have a residual total acid number which increases with use and twice the initial value is usually taken as a criterion to change the oil.

The present TBN results for the Ford 1.8 litre IDI diesel engine and the Austin taxi are shown in Fig. 16. The results without the recycler showed a much greater fall in the TBN with lube oil age than with the recycler fitted. For the Ford engine the time for the TBN to be reduced to 10 was doubled using the recycler. The lube oil used in the two tests had different base TBN but both oils had a similar relative deterioration in TBN with oil age. This is shown in the normalised TBN results in Fig. 17 which shows that the two engines had a very similar behaviour in terms of the TBN reduction as a function of age with and without the recycler fitted.

The results for the Cummins C6 bus engine are shown in Fig. 18 and the normalised results are shown in Fig. 19. Without the recycler the oil TBN deteriorated to an unacceptable number of 2 after 400 hours, but with the oil recycler fitted the TBN had deteriorated to only 6 after 1700 hours. These results were quite remarkable and were checked with a different oil and ageing test and a similar small deterioration in the TBN was found over 1400 hours, as shown in Fig. 20. The three engines used in this study without the recycler fitted had a deterioration in TBN that was typical of that reported by others (2, 3), as shown in Fig. 21.

The TBN results from the Cummins L10 and Gardner 6LXB engine fleet trials are shown in Fig. 22. In these tests the oil was aged until the normal oil change mileage and then the recycler was fitted, but the oil was not changed as it was in the above tests. The results show that there was a reduction in the TBN up to the 8,000 mile normal oil change, but once the recycler was fitted there was only a small further deterioration in the TBN. These tests were carried out with the normal engine oil top up, which is the reason for the increase in TBN with the Cummins L10 engine.

FIG.13 OIL'S CARBON CONTENT BY TGA

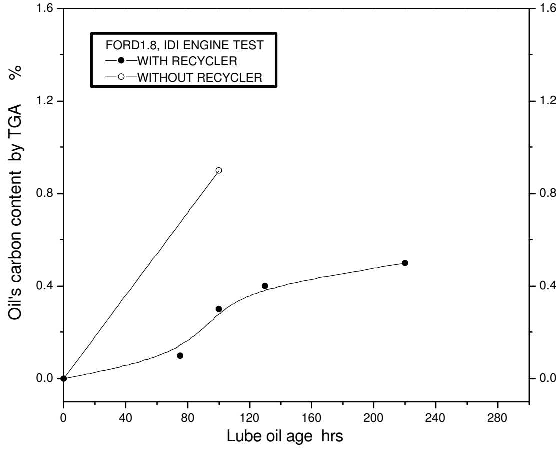


Fig.14. SOOT CONTENT OF THE OILS ON THE BUS TEST

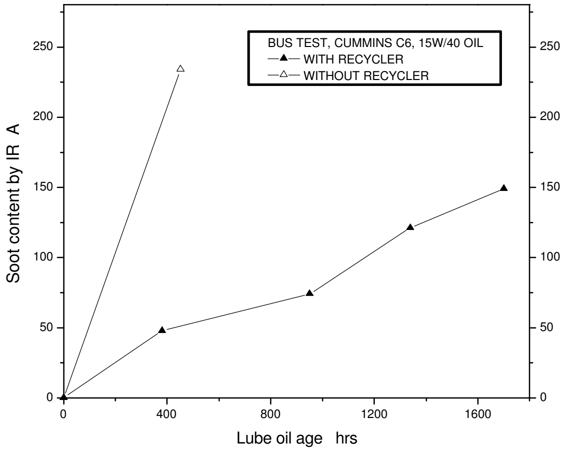


FIG.15 ZDDP CONSUMPTION RATE IN THE USED OIL

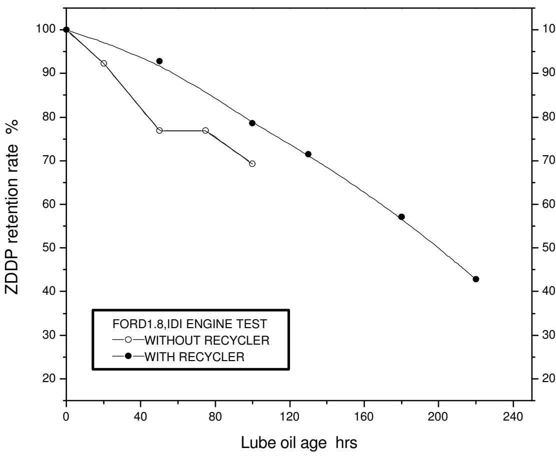


FIG.16 OIL'S TBN RETENTION ON TAXI AND FORD1.8 IDI ENGINE TEST

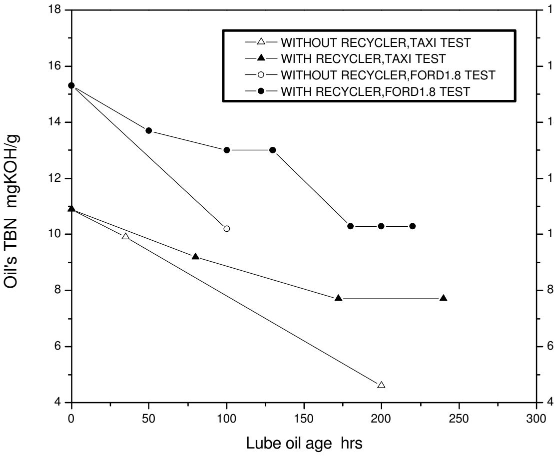


FIG.17 TBN RETENTION RATE ON TAXI AND FORD ENGINE TESTS WITH AND WITHOUT THE RECYCLER

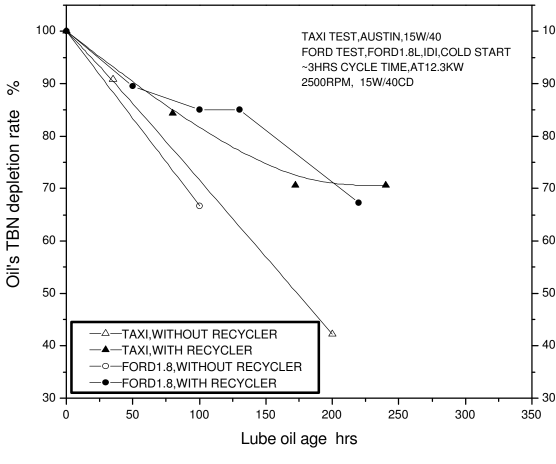
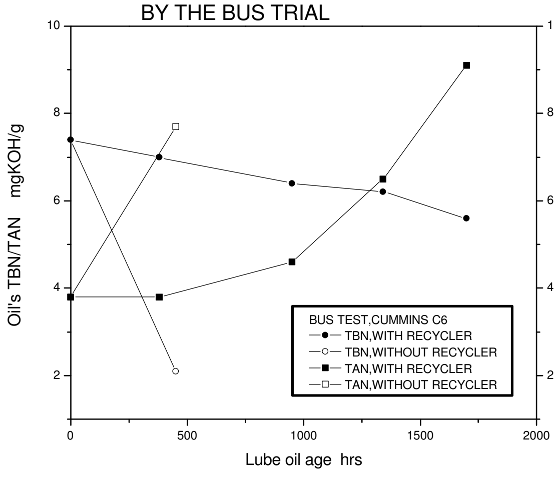


FIG.18 TBN RETENTION/TAN INCREASE RATE BY THE BUS TRIAL



The TAN results for these engines are shown in Fig.23 and these show similar results to those for TBN. There was an increase in TAN to double the initial value at the normal oil change mileage. However, when the oil recycler was fitted there was no further deterioration in the TAN.

The TAN results for the Ford and Austin taxi engines are shown in Fig. 24. For both engines the increase in the TAN was substantially reduced when the oil recycler was fitted. The relative effect was greater in the older Austin taxi engine then in the more modern Ford engine, as shown in Fig.25.

The Cummins C6 TAN results are shown in Fig. 18. The TAN increased to twice its initial value at the normal oil change period of 400 hours. With the oil recycler fitted this increase was drastically reduced and took 1500 hours to reach the TAN level that was reached in 400 hours without the recycler. These results are shown normalised to the initial TAN value in Fig. 26. Comparison with Fig. 25 shows that there was a greater improvement in the TAN deterioration for the Cummins C6 engine than for the Ford or Austin taxi. These three test engines had different rates of TAN deterioration, but the normalised results were similar to the trends reported by Miyahara et al. (11) for four different oils, as shown in Fig. 27.

Wear Metals in the Aged Oil – The cleaner oil with less soot using the bypass filter results in a lower depletion rate of the anti-wear additive ZDDP, as detailed above. This should result in lower engine wear. Also the cleaner oil forms lower in cylinder deposits and allows existing deposits to be burnt away in the engine. These lower deposits will also result in less valve, piston ring and liner wear. All the results for wear metals in the used oil for all the engine trials, shown in Figs 28-39, demonstrate that the recycler acts to reduce wear metals in the oil and hence reduces engine wear.

Fig. 28 shows the lube oil iron content for the Ford IDI tests and the Austin Taxi tests. Sources of iron in engine wear debris are from the cylinders, gears, crankshaft, camshaft and bearings. The oil recycler had the greatest influence on oil iron content in the taxi, with the iron reduced by about two thirds at 220 hours. For the Ford engine tested on the stop start cycle the oil iron content was reduced by about 50% at 100 hours using the recycler. None of the iron contents in Fig. 28 are of concern as 100 ppm iron is the usual level at which a warning is issued in oil condition monitoring and 200 ppm is a typical oil condemnation limit (34,39).

The Cummins C6 bus results in Fig. 29 also show a marked reduction in the oil iron content using the recycler. At the normal oil change interval of 400 hours the iron content was reduced by 50%, a similar reduction to the Ford IDI engine test results. Also after 1700 hours of use with the recycler fitted the iron content had only just reached the limit at which an oil quality warning is issued on the basis of the iron content being excessive.

Cooke (8) also reported the influence of oil age on wear metals over a 300 hour test on a DDC Series 60 engine with no oil top up, for two piston compression ring designs. Their results showed that the iron content increased to 100 and 80 ppm after 300 hours and the increase was nearly linear with time. After 100 hours the iron content was 35 and 20 ppm. These are comparable with the present baseline results without the recycler in Figs. 28,29 and 36.

Chromium in engine oil usually comes from cylinder liners, piston rings and rolling element bearings. The present results for oil chromium levels are shown in Fig.30 for the Ford IDI and Austin taxi tests and in Fig. 31 for the Cummins C6 tests. For all the tests the recycler reduced the chromium in the oil. The reduction was greatest for the Austin taxi (78% at 100 hours) and least for the Ford engine (40% reduction at 100 hours) and intermediate for the Cummins C6 at 60% at 350 hours. A warning level limit of Chromium in oil is 10ppm (34,39) and a condemned limit is 30 ppm (34). In none of the tests was the 10ppm limit reached, although after 17000 miles with the recycler the Cummins C6 engine was just approaching 10ppm in the oil.

Lead in used oil arises from bearing wear and from greases and paint, the main source in the present work is likely to be from bearing wear. A warning limit on oil lead content is normally issued at 25 (39) -30 ppm (34) with a condemned oil limit of 60ppm lead. The present lead results are shown in Figs 32 and 33 for the Ford, Austin taxi and the Cummins C6 engines. For all three engines fitting the recycler reduced the oil lead content for the same oil age, indicating a reduction in bearing wear. In none of the tests was the minimum wear limit of 25ppm reached.

At 100 hours the lead was reduced by 73% with the recycler for the Austin taxi tests and 53% for the Ford engine. For the Cummins C6 engine at 450 hours the lead was reduced by 87% and even after 1700 hours with the recycler fitted the lead content was only 13 ppm. Cooke (8) reported lead wear metal data in oil for a DDC Series 60 engine for two piston compression rig designs. The test was carried out over 300 hours with no oil top up. The results showed a near linear increase in lead in the oil with time and a peak value after 300 hours of 100 and 165 ppm and 30 and 70 ppm after 100 hours. Comparison with the present results in Figs. 32,33 and 38 shows values well below these levels without the recycler fitted, which could mean that the present engines had less bearing wear than the DDC engine.

FIG.19 TBN RETENTION COMPARISON BY THE BUS TRIAL

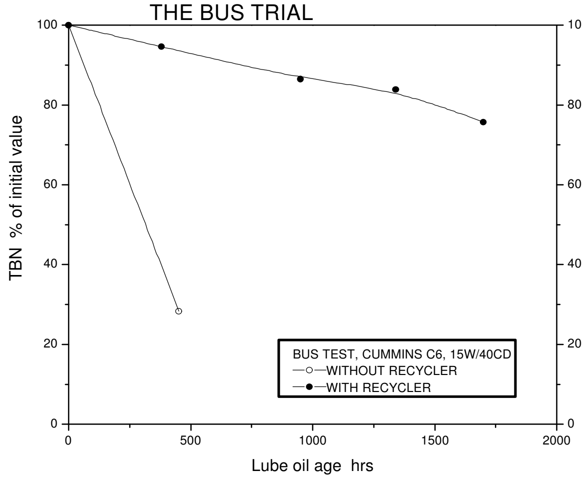


FIG.20 TBN DEPLETION FROM DIFFERENT OILS

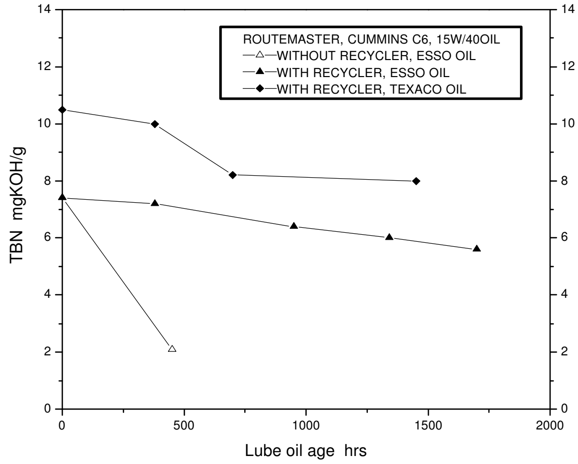


FIG.21OIL'S TBN DEPLETION RATE ON SOME DIESEL ENGINE TESTS

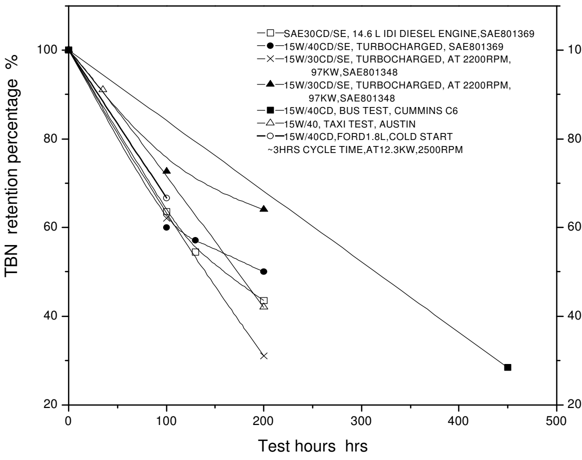


FIG.22 TBN DEPLETION FROM DIFFERENT ENGINES ON BUS TESTS

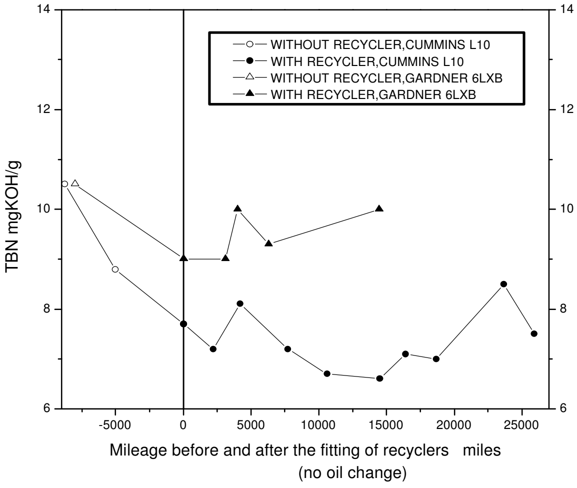


FIG.23 TAN INCREASE FROM DIFFERENT ENGINES ON BUS TESTS

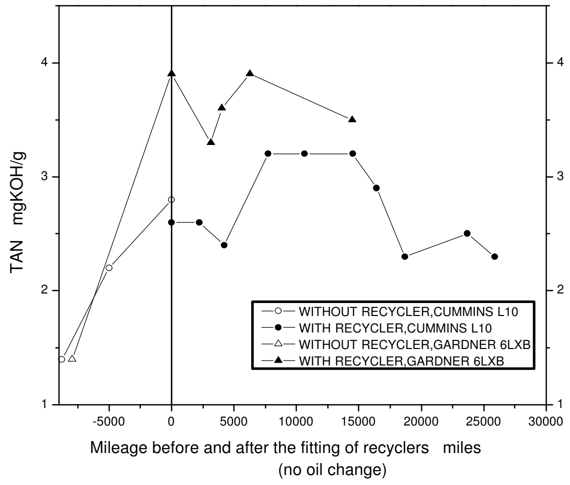
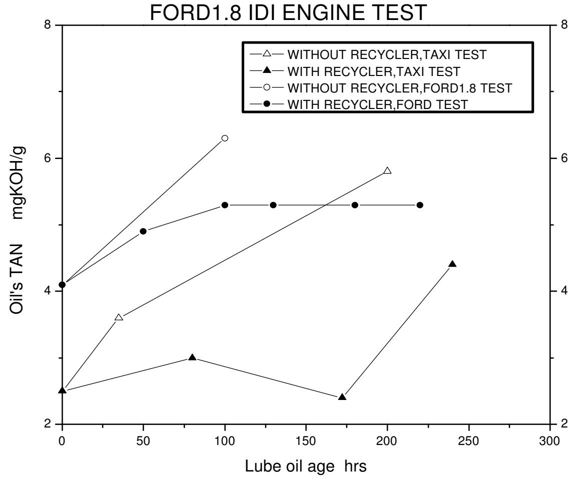


FIG.24 OIL'S TAN INCREASE ON TAXI AND FORD1.8 IDI ENGINE TEST



Copper in oil can arise from wear on bearings and worn gears and the limits that the oil would be reported at being a problem are 20 (39)-30 ppm(34) and oil is normally condemned at 60 ppm copper. The present copper results are shown in Fig. 34 and 35 for the Ford, Austin Taxi and Cummins C6 bus tests. In all three cases the fitting of the recycler resulted in a large increase in the copper in the oil. For the Ford and Cummins C6 tests the copper levels increase to the level where the oil would be condemned if the copper had originated from engine metal wear.

All the other wear metal results show that wear was decreased by the recycler and hence there had to be a source of copper in the recycler to explain the increased copper in the oil. The source of this additional copper is attributed to be the dome heater which includes copper in its construction. The oil should not be in contact with the copper, but in practice it must be as this is the only copper in the recycler construction. The dome heater construction will be modified in the future to remove the copper.

The Cummins L10 and Gardner 6LXB results for the wear metals are shown in Figs. 36-39. These engines were tested differently and the oil was aged without a recycler up to the normal oil change period, then the recycler was fitted but the oil was not changed and the engine continued to operate. The results have been plotted with time zero as the time of fitting the recycler and the operating time without the recycler after the clean oil change is plotted as negative time. All the results showed a rapid increase in the oil metal content before the recycler was fitted followed by a much lower rate of increase in lube oil metals after the recycler was fitted, apart form copper, which continued to increase.

The Cummins L10 was tested for 25,000 miles without an oil change after fitting the recycler (32,000 miles since the last oil change). At the end of this period none of the wear metals were near the normal warning limit. This confirms the TAN and TBN results reported earlier that the oil was still in a useable state after 32,000 miles with the recycler fitted for the last 25,000 miles. This is an oil life extension that is over 4 times the original life with the recycler fitted and hence the oil change period could be drastically increased using the recycler.

The Gardner engine was older than the Cummins and the wear metals at the normal oil change period were much higher than for the Cummins C6 engine. However, on fitting the recycler there was little further deterioration of the oil wear metals. The oil quality after 15,000 miles with the recycler (23,000 miles oil age) was still satisfactory and there were no oil quality parameters that indicated the oil should be changed. The monitoring of this test ceased at 15,000 miles and the final oil life is not known but the 15,000 miles with the recycler is twice the normal oil change period. However, the recycler test was not with fresh oil and hence the oil life with the recycler will be at least three times the normal oil change period for this engine.

OIL ADDITIVE METALS – Oil additives for detergency, antioxidation and dispersency actions contain the metals calcium, zinc and phosphorus. These elements in the lube oil were analysed for the Ford and Austin Taxi tests and the results are shown in Figs. 40-42. None of these results showed a major decrease in oil additive metals during the period of the test and this was also found by Cooke (8). Cooke showed that additive metals could increase during tests with no oil top up. The reason was that the consumption of oil reduced the oil sump volume and this increased the concentration of the additive if none had been consumed.

The recycler had no consistent influence; for the Ford engine the recycler increased the calcium relative to the results with no recycler, but for the taxi engine the reverse occurred. Calcium also increased significantly in the initial test period for the Cummins C6 tests, as shown in Fig. 43. The other additive metals also had similar trends to calcium. There was little evidence that the bypass filter used in the present work could filter additives out of the used oil as well as particulates.

OIL CONSUMPTION – A low diesel engine oil consumption is an important design method to reduce particulate emissions. The oil consumption was determined from the Ford engine tests by the drain and weigh technique, taking into account all the oil samples removed for analysis. The fuel dilution of the oil was also determined and the oil consumption corrected for this. The average oil consumption over the 220 hour test period with the recycler fitted was determined as 0.23 g/KWHr or 0.075% of the fuel consumption.

Unfortunately, in the tests without the oil recycler the test was prematurely ended by an unauthorised oil top up that was not quantified and hence the oil consumption could not be determined by the drain and weigh technique. Instead the all consumption was determined by the oil calcium balance technique. This is based on an analysis of the calcium in the oil and the calcium on the particulate filter paper and is fully detailed in Ref. 20. At the 2500 rpm 12 kW condition of the present work the oil consumption of the Ford engine without the recycler was 0.20% of the fuel, a factor of 2.7 increase on the oil consumption comparing with the recycler fitted. The reduced fuel dilution with the recycler was one factor that contributed to this reduced oil consumption.

FIG.25 OIL'S TAN INCREASE ON TAXI AND FORD1.8 IDI ENGINE TRIALS

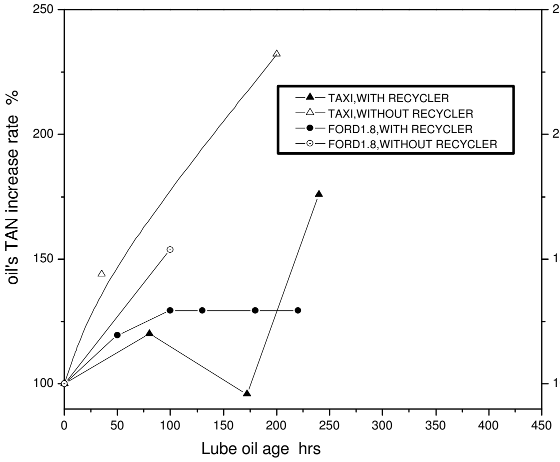


Fig.26 TAN INCREASE RATE ON THE BUS TRIAL WITH AND WITHOUT RECYCLER

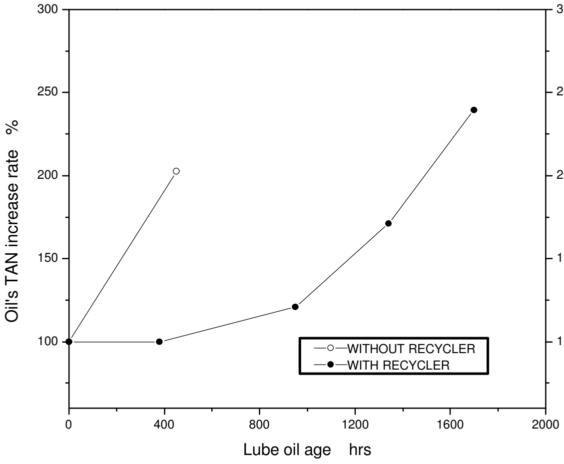


FIG.27 TAN TRENDS OF USED OILS FROM LITERATURE TESTS(WITHOUT RECYCLER)

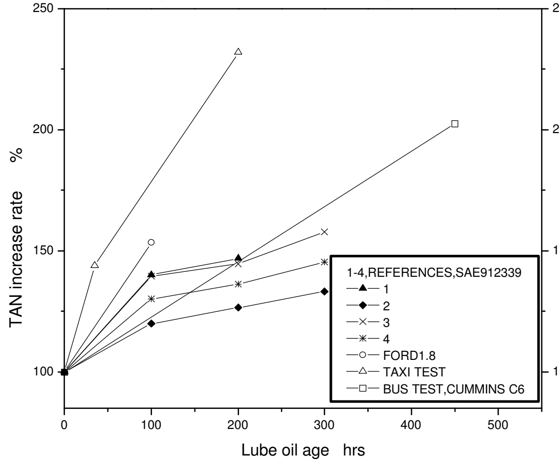


FIG.28 USED OIL'S IRON CONTENT ON FORD1.8 AND TAXI TESTS

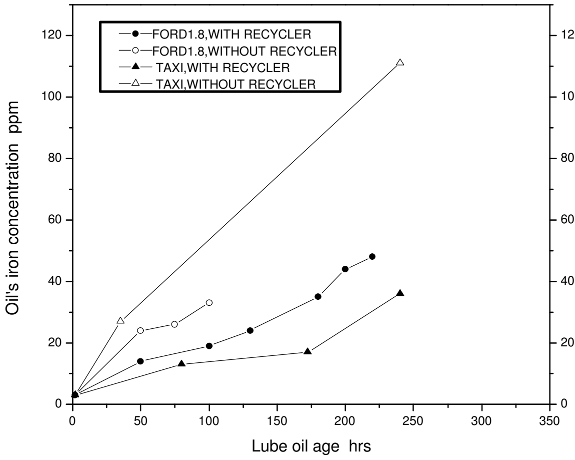


FIG.29 USED OIL'S IRON CONTENT ON BUS TEST

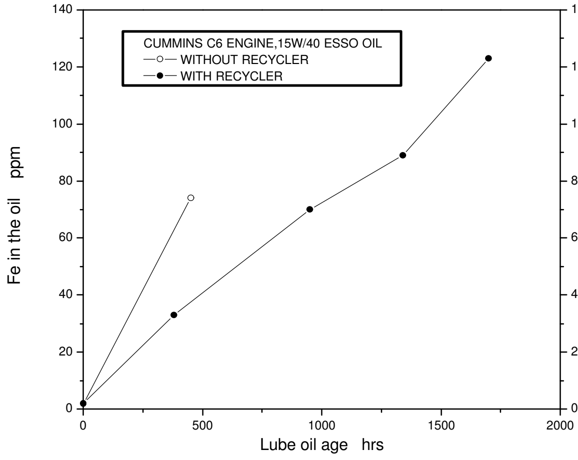


FIG. 30 OIL'S CHROMIUM CONTENT ON FORD1.8 AND TAXI TESTS

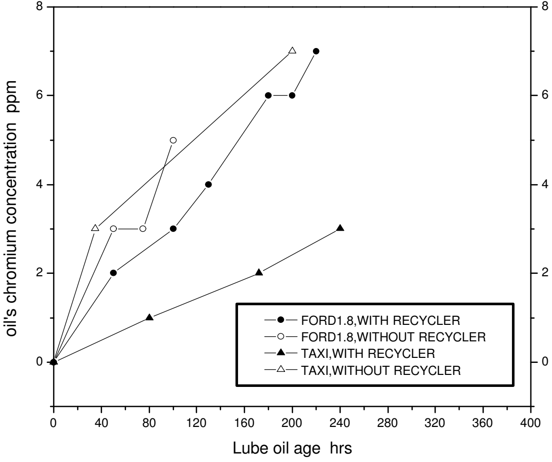


FIG.31 USED OIL'S CHROMIUM ON BUS TEST

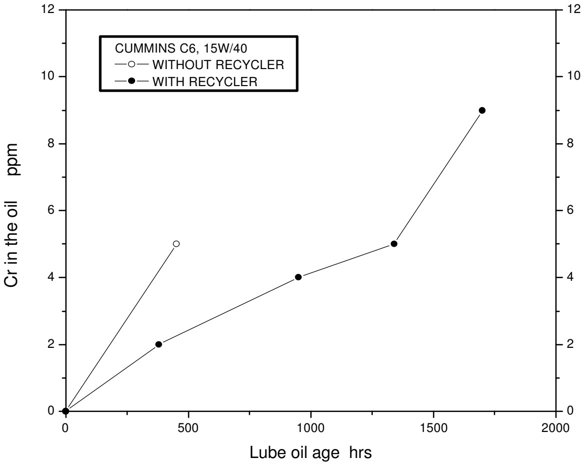


FIG.32 USED OIL'S LEAD CONTENT ON FORD1.8 AND TAXI TESTS

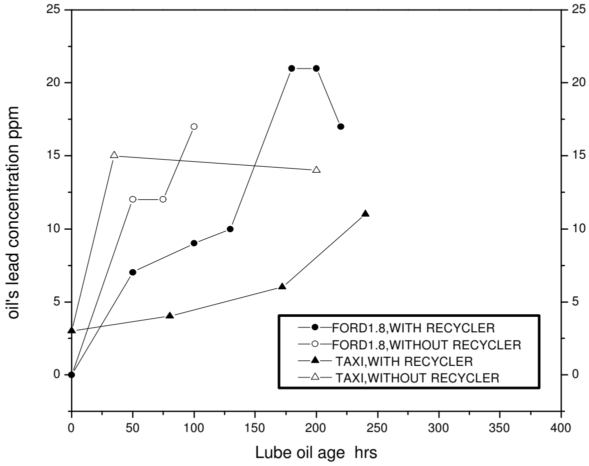


FIG.33 USED OIL'S LEAD ON BUS TEST

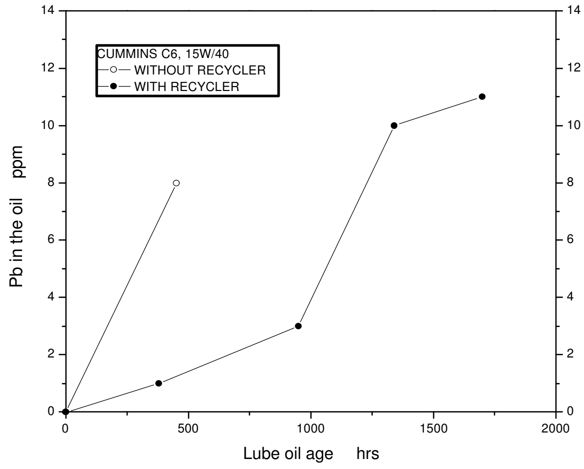


FIG.34 USED OIL'S COPPER CONTENT

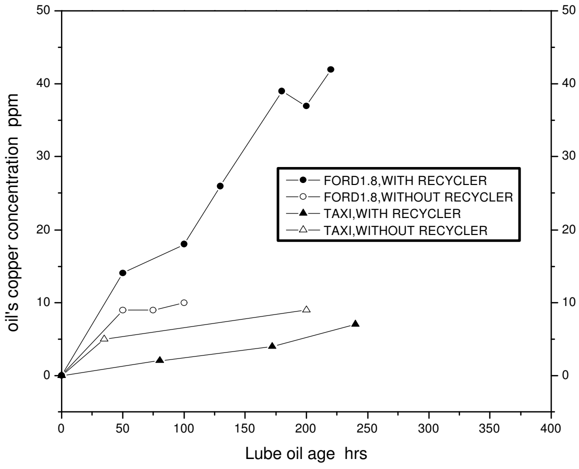


FIG.35 USED OIL'S COPPER ON BUS TEST

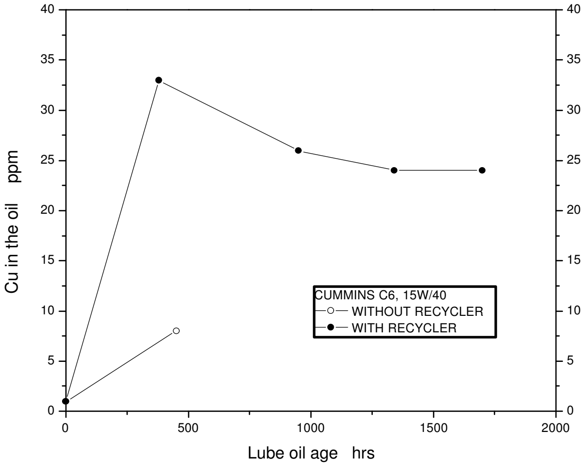


FIG.36 IRON CONTENT VARIATION BEFORE AND AFTER FITTING OF THE RECYCLER ON BUS TEST

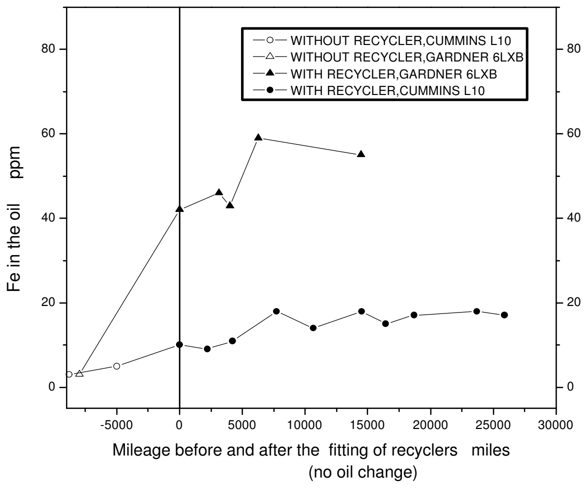


FIG.37 CHROMIUM CONTENT VARIATION BEFORE AND AFTER THE FITTING OF RECYCLERS

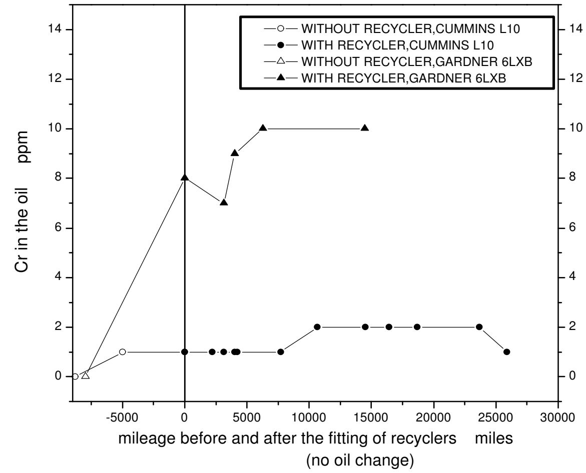


FIG.38 LEAD CONTENT VARIATION BEFORE AFTER THE FITTING OF RECYCLERS

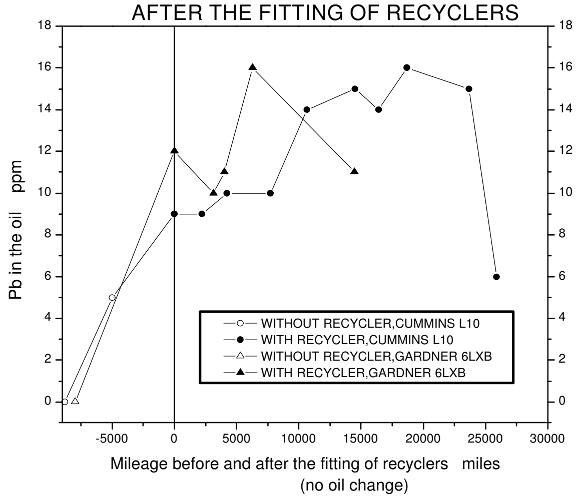


FIG.39 COPPER CONTENT VARIATION BEFORE AND AFTER THE FITTING OF RECYCLERS

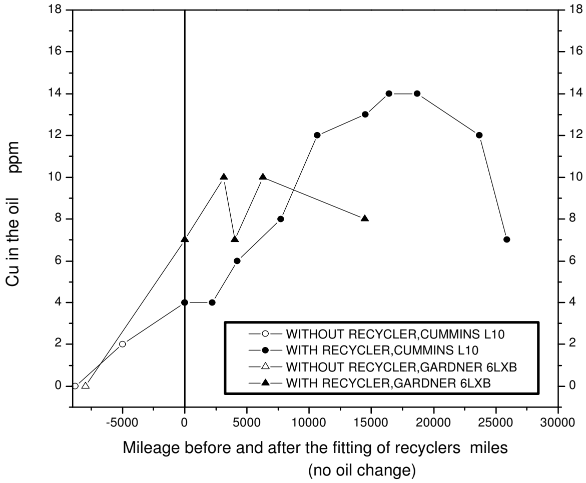


FIG.40 CALCIUM IN THE OIL ON TAXI AND FORD1.8 TESTS COMPARING WITH RERERENCES

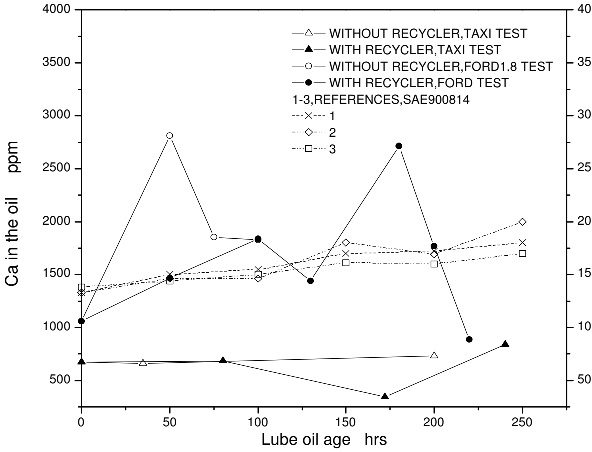


FIG.41 ZINC IN THE OIL ON TAXI AND FORD1.8 TESTS COMPARING WITH REFERENCES

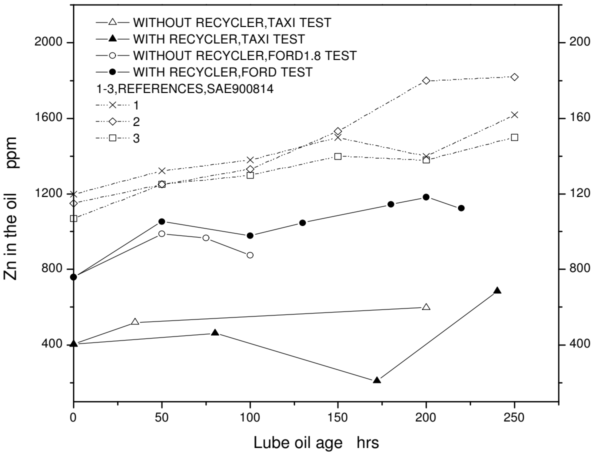


FIG.42 PHOSPHORUS IN THE OIL ON TAXI AND FORD1.8 TESTS COMPARING WITH REFERENCES

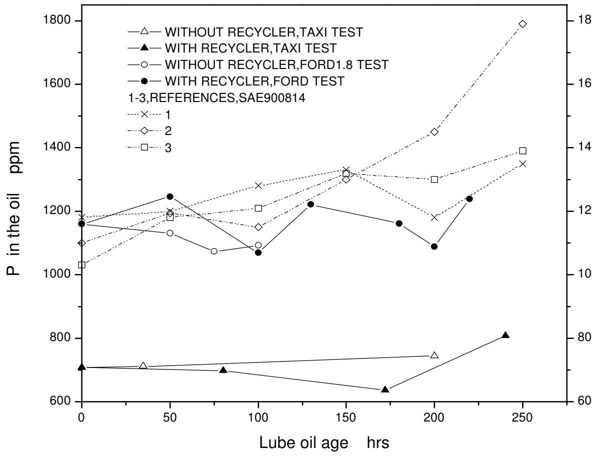
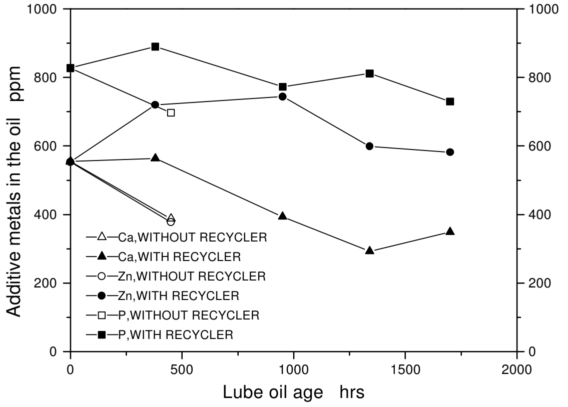


FIG.43 ADDITIVE METALS ON THE BUS TEST



CONCLUSIONS

1. An oil recycler, which combines a 5-6 micron bypass filter with a 135C infra red heated dome has a combined action of removing particulate material from the used oil onto the bypass filter and removing water and volatile oil and fuel dilution components at the heater. The combined action gives on-line cleaning of the oil and a greatly extended life.
2. A 1.8 litre Ford passenger car IDI diesel with EGR for NOx control was tested, with and without the recycler fitted, in the laboratory for 220 hours on a stop start 2.5 hours average cycle time with up to a week of cold soak between some tests. These results showed a significant reduction in the oil fuel dilution and water content using the recycler. There was also a small 5-8% reduction in the fuel consumption.
3. The bypass filter was effective in removing soot from the oil as measured by infra red absorption and by TGA analysis for the Ford engine tests. Carbon in soot was 0.5% after 220 hours with the recycler compared with 0.9% after 100 hours without the recycler.
4. The oil recycler reduced the removal of the wear protection additive ZDDP, due to the reduced oil soot content and the associated absorption of ZDDP onto the soot.
5. The recycler on the Ford engine was shown to decrease the deterioration in TBN with time and to reduce the increase in TAN with time and together this results in a large extension in the oil life.
6. All the main wear metals in the oil were reduced on the Ford engine when the recycler was used.
7. Four on-road vehicle tests were carried out on Cummins C6 and L10 engines in buses, and Austin taxi and a Gardner 6LXB bus engine. All the findings in the Ford engine tests were confirmed in the on-road tests. The extension of the oil life by a factor of four was demonstrated for the Cummins C6, a factor of five for the L10, a minimum factor of three for the Gardner engine. The oil life with the recycler was not determined for the Austin taxi engine and the Ford engine tests are still in progress. It may safely be concluded that with the oil recycler fitted a minimum doubling of the oil life can be achieved, with many applications showing a greater life than this.
8. The recycler on the Ford engine was also shown to decrease the oil consumption rate, thus requiring less topping up of the oil. An oil consumption over the 220 hour test of the recycler on the Ford engine was determined as 0.23 g/KWHr or 0.075% of the fuel. This compares with some of the best oil consumptions published. Without the recycler the oil consumption was 0.20%, giving a factor of three reduction in oil consumption with the recycler fitted.

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