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ABSTRACT

A method of cleaning lubricating oil on line was investigated using a fine bypass particulate filter followed by an infra red heater. Two bypass filter sizes of 6 and 1 micron were investigated, both filter sizes were effective but the one micron filter had the greatest benefit. This was tested on two nominally identical EURO 1 emissions compliance refuse trucks, fitted with Perkins Phazer 210Ti 6 litre turbocharged intercooled engines and coded as RT320 and RT321. These vehicles had emissions characteristics that were significantly different, in spite of their similar age and total mileage. RT321 showed an apparent heavier black smoke than RT320. Comparison was made with the emissions on the same vehicles and engines with and without the on-line bypass oil recycler. Engine exhaust emissions were measured about every 400 miles. Both vehicles started the test with an oil drain and fresh lubricating oil. The two refuse trucks were tested in a different sequence, the RT320 without the recycler fitted and then fitted later and the RT321 with the recycler fitted and then removed later in the test and both without any oil change. The RT320 was also the one with the finer bypass filter. The test mileage was nearly 8,000 miles both trucks. The air/fuel ratio was worked out by the exhaust gas analysis. The correlation between air/fuel ratio and emission parameters was determined and appropriate corrections were made in the case of that the air/fuel ratio had an effect on emissions. The results showed that the on line oil recycler cleaning system can reduce the rate of increase of the NOx with oil age. There appeared little influence of the oil recycler on carbon monoxide and hydrocarbon emissions. The rate of increase in particulate emissions was reduced by 50% for RT320 and an immediate decrease in particulate emissions was seen on RT320 test after fitting the recycler. The black smoke was reduced by 30% for RT320 in terms average value and an immediate decrease in smoke after fitting the recycler on RT320 test and an immediate increase in smoke after the removal of the recycler on RT321 test were shown.

INTRODUCTION

Lubricating oil forms a significant fraction of the particulate volatile fraction and can contribute to the carbon emissions. Lubricating oil also acts as a sink for carbon emissions (1,2) and unburned diesel fuel and this can lead to the deterioration of the oil (3), which results in an increase in the particulate emissions (1). For a low particulate emissions engine the work of Cooke (4) showed that lubricating oil may contribute more to the carbon emissions than to the solvent fraction at some engine conditions. His results showed that there was a variable influence of lubricating oil with no influence on particulate emissions for some engine conditions and up to a 250% increase with lube oil age for other engine conditions.

Diesel engines with low particulate emissions have a very low lubricating oil consumption. There is a concern that carbon particles may accumulate to a greater mass concentration in the lube oil, as there will be a reduced dilution with top up of the oil (5). High carbon in the lube oil may then increase the contribution of the oil to the particulate emissions through the associated higher viscosity. Andrews et al (6) have shown that a Euro 1 passenger car diesel engine accumulated carbon in the oil at a greater proportion of the carbon emissions than for an older high carbon emitting engine.

The control of combustion chamber deposits (CCD) in modern diesel engines is recognised as a part of low emission engine design. The extended service requirements are making the control of CCD increasingly difficult (7). The primary source of piston deposits is the lubricant (8) and oxidation of the lubricant is the primary cause of deposit formation (9). In cylinder deposits consist of ash from the lube oil additives, carbon and absorbed unburned fuel and lubricating oil (8, 10). The CCD can be a source of wear in engines, increased friction and hence increased fuel consumption. Crownland heavy carbon has been shown to increase oil consumption (11) and deposits have been shown to increase as piston temperature increases above 250C (12). Deposits also increase with the soot content of the oil (12) and hence deposits can increase as the oil ages. The increased soot in oil as it ages results in an increased oil viscosity (13) and this increases the oil (14) and fuel consumption. The aim of the present work was to examine these influences for two Euro 1 refuse trucks fitted with Perkins engines and to determine the improvement in oil quality through the use of on line recycling of the oil to remove soot, wear metals, fuel and water dilution (3). The recycler had a fine bypass oil filter and an infrared heater to distil out water and light fuel fractions. 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.

Andrews et al (1, 6) showed that the lubricating oil age could have a significant influence on particulate emissions. Three IDI engines were tested over 100 hours to investigate the influence of lubricating oil age on the emissions. Two Ford engines, 1.6 and 1.8 litre, were low emission engines and the Petter AA1 engine was an older technology high emissions engine. For all three engines there was little influence of lubricating oil age on gaseous emissions. There was evidence in the NOx emissions for the Petter and Ford 1.8 litre engines of an action of deposit removal, which reduced the NOx and deposit, build up that increased the NOx. This was also supported by the lube oil additive metal analysis. The hydrocarbon emissions increased with oil age for both of the low emission engines but only the 1.6 litre Ford engine showed a similar change in the particulate VOF. The 1.8 litre engine VOF trends were dominated by lube oil influences, which do not contribute to gaseous hydrocarbon emissions at a 180C sample temperature. The particulate emissions trends with oil age were quite different for the Ford 1.6 and 1.8 litre engines, with a continuous increase in emissions for the former and a decrease followed by an increase after 50 hours for the latter. The Petter engine also followed similar trends to the Ford 1.8 litre engine, although with much higher emission levels. It was shown that these trends were also reflected in the carbon fraction and unburned fuel fractions of the particulate VOF for the two Ford engines. However, the lube oil fraction decreased substantially over the first 50 hours for the Ford 1.8 litre engine and then remained at a stable level. The implication was that the fresh lubricating oil resulted in high unburned lube oil particulate VOF emissions and also generated carbon emissions. Once the volatile fraction of the lube oil had been burnt away in the engine, the lube oil VOF remained stable and the subsequent increase in the particulate emissions was due to increasing carbon emissions. The initial decrease in the fuel VOF fraction followed by an increase after 50 hours was possible due to the initial removal of CCD by the fresh lubricating oil followed by a build up of fresh deposits as the oil aged. Fuel fraction VOF can be contributed to by deposit absorption and desorption, which is a function of the extent of the CCD.

These works is concerned with a technique to keep oil clean, extend its life and reduce the increase in emission that occurs with aged oil. The above review has emphasized the importance of CCDs in emissions and lubricant quality. At the same time as diesel 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, 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 (7). 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 (7). The primary source of piston deposits is the lubricant and lubricant oxidation is the primary cause of deposit formation (7). Diesel engine deposits also increase with the oil consumption (8), the piston temperatures (12) and the oil soot content (12). Engine deposits are a source of unburned hydrocarbons through absorption and they also act as a cylinder insulation, which increases NOx emissions because of the higher cylinder temperature (16).

THE ON LINE OIL RECYCLER AND REFUSE TRUCK TEST PROCEDURE

A method of continually cleaning the engine oil on line was investigated. This was based on the combined effects of a bypass fine oil particulate filter with a 1 or 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. The previous work using this system (3) used a 6 micron bypass oil filter and this was the filter used in RT321 at the start of the present work. However, work was in progress to develop a finer I micron bypass filter and this had reached the prototype stage when it was decided to fit a recycler to the second refuse truck (RT320). It had originally been intended in the present work to use two nominally identical refuse trucks with the same engine and mileage. However, as will be shown in the results, the two refuse trucks had different oil deterioration rates and the accompanying emissions results showed different emissions. RT321 was operated consistently 2 units richer in air/fuel ratio than RT320 for the same duty cycle and journey with an average air/fuel of 33/1. Soot accumulation in the oil and lube oil consumption for RT321 were also significantly higher. Consequently, it was concluded that RT321 was in a worse mechanical state to RT320 and the two refuse trucks could not be compared one with a recycler and one without. Thus, both refuse trucks had to be tested with and without the recycler.

RT320 was first tested without the recycler fitted and after 4,700 miles a recycler with the 1 micron bypass filter was fitted without any oil change. RT321 was first fitted with a recycler with the 6 micron bypass filter and after 5,000 miles the recycler was removed without any oil change.

The refuse trucks were operated 6 days a week with an average mileage per day of about 30 miles. However, the engines of refuse trucks were kept in high power output during their work for loading/unloading the rubbish and the refuse trucks had a frequently stop-start duty cycle. These made the engines of refuse trucks work under a severe condition and accelerated the engine oil deterioration, which resulted in increases of engine CCD and thus increase emissions.

One of the advantages of the recycler is that it provides for an improved oil quality and reduced oil consumption (3). The improved oil quality reduces the engine CCDs. Thus the reduced oil comsumption and CCD in the combustion chamber reduce engine emissions. Authors have shown that emissions had been reduced for a Ford1.8 litre IDI engine test as a result of improved oil quality and reduced oil consumption(15).

Other investigators of bypass filters have advocated the improvement by using filters of the order of 1 micron (22-26). The initial choice in the present work of 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. Also, very fine 1 micron oil filters that were available from hydraulic oil filter manufacturers had a rather high pressure loss. If these were used in the recycler then the bypass flow would have been controlled by the filter pressure loss and the flow rate would have decreased as soot built up in the filter. A key feature of the present recycler is that the bypass oil system oil flow rate is relatively high. In the Ford 1.8 litre IDI passenger car diesel tests (3) the recycler oil flow rate was such that oil the sump volume of the oil was passed through the recycler four times an hour. The one micron by pass filter used in this work was developed to have a fine filtration of 1 micron particles without affecting the recycler bypass flow rate, even when loaded with soot. The present results show that this new fine filter does improve the performance of the recycler. This filter is now in production and will be used in the future commercial use and evaluation work using this system.

Bypass filters have two basic features: a high filtration efficiency and a high particulate storage capacity (24). They reduce the fine particulate matter in the oil leaving the main filter to remove the larger particulates. Stenhouer (25) showed that bypass filters removed organic material, sludge, varnish, resin, soot and unburned 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 (26). The benefit of bypass filtration was the 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 (24) with the flow between the two splitting according to their flow resistances.

Although a filter based bypass filter was used in the present work, centrifugal bypass filters are also quite common (26). 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 (26).

Centrifugal filters have an effective particle size removal below 1 micron and have a filtration efficiency that does not deteriorate with time (26). They are generally more expensive initially than filter based bypass filters. One assessment of bypass filters (27) 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 6 and 1 microns.

EXPERIMENTAL TECHNIQUES

ENGINE SPECIFICATIONS - The two refuse trucks tested had the same engine specification that is detailed in Table 1 and operated with routine oil top ups and normal commercial duty cycles. The oil and exhaust gas samplings were taken every two weeks, at an interval of about 400 miles. The same route and driver were used for each test run. However, traffic conditions were varied.

RT320 started the test without the recycler fitted and RT321 started the test with the recycler fitted. For RT320 after 4,700 miles after the commencement of the test with fresh oil, a recycler was fitted. Then the test continued for 3,000 miles. For RT321 after ~5,000 miles after the commencement of the test with fresh oil, the recycler was removed and the test continued for 2,600 miles without the oil being changed. As discussed above, RT320 was fitted with a recycler with a bypass particulate filter size of 1 microns and RT321 was fitted with a 6 micron filter.

FUEL AND LUBRICATING OIL - The fuel used in the tests was commercially available standard low sulphur diesel with sulphur content ≤ 0.05%.

The lubricating oils used in tests were 15W-40 CE/SF mineral oil. The specifications of diesel fuels and lubricating oils are reported in a separate SAE paper.

PARTICULATE SAMPLING SYSTEM - A stainless steel tube (gas sampling tube) with a diameter of 7 mm was inserted into the centre of the tailpipe before the muffler (about one meter from the exhaust manifold). This tube was connected to a relay tube (about 2 meters long stainless steel tube) which was terminated beneath the driver cab and bolted with a stopper when the vehicle was in service. In the case of sampling, a 2 meter rubber tube was used to connect relay tube and the sampling kit which was placed in the cab. Thus the exhaust gases were conducted into the sampling kit. After the completion of the sampling the rubber tube was taken off and the relay tube was blanketed so as not to interfere with the refuse trucks in service.

Table 1. Specifications of the engines

	Refuse truck
Type	Perkins Phazer 210Ti
Maximum Power Rating	156.5KW(210BHP) AT 2500rpm
Displacement litre	6.0
Oil pressure, low idle(min)	
at2100rpm(max)	43-49 P.S.I
Oil capacity litre	18
Bore mm	100
Stroke mm	127
Cylinder No.	6
Compression ratio	17.5:1
Lube oil change intervals	3 months
EGR	
Aspiration	Turbocharge intercooled

The exhaust gases from the rubber tube were conducted through a 125ml wash bottle placed in an ice bucket to condense the water and heavy hydrocarbons and then passed to a filter block with a 47 mm Whatman Glassfiber filter paper to collect the particulate samples. The residue gases were then passed through a gas meter to count the volume of gases and a flow meter, and finally collected in a gas bag. This sampling process was driven by exhaust pressure. Therefore the samples collected were proportional to combustion pressure and represented real driving conditions.

GAS ANALYSIS - The exhaust gases collected in a 60 litre gas sample bag were analysed as soon as possible after sampling. The gases were passed to an oven and then transported to a heated FID at 180°C for total hydrocarbon analysis, a heated Chemiluminescence NOx analyser for NOx analysis, a Servomex paramagnetic analyser for oxygen analysis and a Hartman & Broun Uras 10E for CO and CO_2 analysis. The air/fuel ratio could be worked out by these gas analyses according to carbon balance principle.

PARTICULATE ANALYSIS - The particulate filter papers were conditioned in a constant humidity enclosure for 24 hours before and after the tests and the weights recorded after each 24 hour conditioning period. The increase in weight was the particulate mass and this was measured to 1 microgram accuracy and a minimum mass of 1 mg was collected, giving a minimum resolution of the mass of 0.2%. Only one filter paper was taken at each oil mileage as the driver and vehicle were only available for one test journey.

The particulate was analysed for carbon, fuel and unburnt lubricating oil fraction using TGA. A round cutter with a diameter of 29 mm was used to cut the filter papers so as to get an identical area of the filter paper and minimise the interference of blank filter papers. This cut filter paper sample was wired and hung on a hook on an end of a microbalance enclosed in the oven with nitrogen atmosphere. The sample was heated up to 550°C at a rate of 20°C per minute and kept for 10 minutes where no further weight loss occurred. The weight loss represented the volatile fraction of particulates. The air was then introduced and the temperature was increased to 560°C and maintained for 20 minutes. The weight loss before and after introduction of the air was equivalent to the carbon mass. The rest of the sample was the ash mass of particulates. A blank filter paper was used to determine the weight loss of the filter paper and this was used to correct the particulate weight loss. The TGA procedure has been used for determination of fuel and lubricating oil fractions of particulates and detailed in reference 15.

BLACK SMOKE MEASUREMENT - An OPAX 2000-II smoke meter was used in bus and refuse truck tests. This is a partial flow smokemeter or opacimeter designed for measuring the exhaust smoke of diesel engines. The principal configuration is that it has a heated smoke measuring chamber which contains a light source (halogen lamp), a sensor (silicon photodiode with corrected spectral response similar to the photopic curve of the human eye - peak response 550nm) and a mirror as shown in Fig.3.5. It measures the smoke(opacity) based on the visible light absorption of the exhaust gas as detected by a sensor.

The testing procedure used was the Free Acceleration Smoke (FAS) measurement required by the Vehicle Inspectorate for MOT test. This procedure has good repeatability and considered to indicate the vehicle's actual smoke emission. The details are as follows:

Smoke testing procedure:

-Switch OPAX 2000-II smoke meter on to warm it up.

-At the end of the warm up period the OPAX 2000-II shows dashes on displays.

-Press the MEASURE key. The display shows "REF" and the equipment starts a new autozero. After this, the equipment is ready to operate.

-Start the engine which should already be at running temperature. Depress the accelerator pedal until the engine attains its governed speed and then release the accelerator to idle. Repeat this several times in order to purge the exhaust of loose dust and carbon.

-Insert the probe in the exhaust pipe using the adapter provided. Ensure it is fixed to the tailpipe.

-Press the MEASURE key. When the display is flashing "-1-" the operator can commence the accelerations.

-For each acceleration, the operator depresses the accelerator sharply to full fuel position and on attaining governed speed remains there for approximately 2 sec, then releases the accelerator. The display will delay for 5-6 sec and then prompts the operator for a new acceleration; blinking on the MEASURE display indicates the next acceleration is required.

-Repeat the acceleration and idling procedure for a minimum of six accelerations. An average value of opacity is displayed. Print it out and the test is finished.

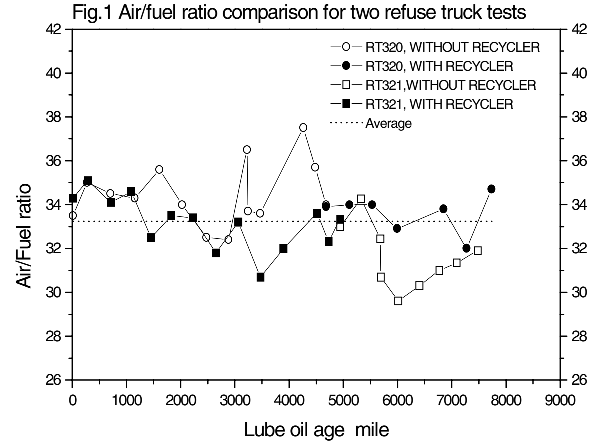
The unit measured by this procedure was K (1/m) from 0.00 to 9.99.

AIR/FUEL RATIO

As the operation of engines could not be the same for every sampling cycle, even for the same route and driver, the air/fuel ratio had to be corrected to the mean air fuel ratio for each test journey. The air fuel ratio was determined by carbon balance from the exhaust gas analysis.

Fig.1 shows the air/fuel ratio for two truck tests. The variation of air/fuel ratio was from 32 to 38 with an average value of 34.2 for RT320 and from 29 to 35 with an average value of 32.3 for RT321. This shows that RT321 had a 2-unit richer combustion condition than RT320. The average air/fuel ratio for two refuse truck tests is 33.2, which was used as a mean air/fuel ratio to correct raw emission results if a good correlation between emission parameter and air/fuel ratio exists.

Fig.1 Air/fuel ratio comparison for two refuse truck tests



The gaseous, smoke and particulate emissions were calculated against the air/fuel ratio using linear regression analysis to determine the correlation between them. The regressed results are shown in Figs.2 and 3. It has shown that the following emission parameters have a significant correlation with the air/fuel ratio:

For RT320: NOx;

For RT321: CO, HC, total particulate mass, particulate ash, particulate carbon, particulate VOF and lube oil VOF.

It revealed that most emission parameters for RT320 were not sensitive to air/fuel ratio whereas in contrast, most emission parameters were correlated to air/fuel ratio for RT321.

GASEOUS EMISSIONS RESULTS

CARBON MONOXIDE - As shown in Figs.2a and 3a, the air/fuel ratio did not have a significant effect on CO emissions for RT320 and yet a notable effect for RT321. Therefore, the CO emissions were corrected to the mean air/fuel ratio for RT321.

The CO emissions for two refuse trucks were shown in Figs.4 and 5. For RT320, without the recycler the CO emissions declined slightly from 240 ppm to 220 ppm with two peaks appearing at around 1,100 miles and 4,500 miles respectively. With the recycler fitted, the CO emissions continued to decrease from 220 ppm to 190 ppm after 1,300 miles using the recycler. Then two consecutive peaks in CO emissions appeared followed by falling back to 190 ppm. The first peak appeared at 1,100 miles was associated with a fall in NOx emissions and a peak in hydrocarbon emissions shown in Figs.7.48 and 50, which could be explained as due to low temperature in combustion chamber. The other peaks were not mirrored in NOx and hydrocarbon emissions and could be due to traffic variations. For RT321, without the recycler the CO emissions fluctuated with an increasing trend (from 360 to 390 ppm in 5,000 miles) with oil age. With the recycler removed, the raw data were showing a higher CO emissions. However, as CO emissions were affected by the air/fuel ratio, the data was corrected to the mean air/fuel ratio and showed that CO emissions were at a similar level. Comparing two refuse trucks, it could be found that refuse truck RT321 had higher CO emissions (about 150 ppm higher) than that for RT320. This indicated that the combustion process in the RT321 engine was more incomplete.

HYDROCARBONS - The total gaseous hydrocarbon emissions were correlated to the air/fuel ratio only for RT321, as shown in Figs.2b and 3b. Thus the raw data for RT320 and air/fuel ratio corrected total hydrocarbon emissions for RT321 were shown in Figs.6 and 7.

The hydrocarbon emissions decreased with oil age generally for RT320 without the recycler. There was a peak at about 1,100 miles of oil age. This peak in HC emissions was corresponding to a peak in CO emissions and a fall in NOx emissions at the same time. This indicated that the temperature in the combustion chamber at this point was low and thus gave rise to a low NOx but high CO emissions and HC emissions. This is a typical example of emission variation due to traffic variation. With the recycler fitted, the total gaseous hydrocarbon emissions continued to decrease until 6,000 miles of oil age, followed by an increase after 6,900 miles, which was co-ordinated with an increase in CO emissions at the same time. The reason for this increase was not very clear, possibly due to large amount of oil top up and traffic variation. Generally, the fitting of the oil recycler did not alter the gaseous hydrocarbon emissions for RT320.

The total gaseous hydrocarbon emissions from RT321 test with the recycler fitted showed a generally constant level with some fluctuations. After the recycler was taken off, hydrocarbon emissions had a large increase after 800 miles, where the hydrocarbon emissions were almost doubled, followed by a rapid fall. Another large peak in hydrocarbon emissions appeared after 1,300 miles. This refuse truck had a very high smoke emissions, as shown below, and a high lube oil consumption. Hence it must have some mechanical faults in its engine. These two peaks in hydrocarbon emissions could be due to excessive unburnt lube oil.

NOx EMISSIONS **-** The NOx emissions were sensitive to the air/fuel ratio for RT320 and yet not sensitive to the air/fuel ratio for RT321 as shown in Figs.3c and 3c. Hence NOx emissions were corrected to the mean air/fuel ratio for RT320. Figs.8 and 9 show the raw and corrected NOx emissions for two refuse trucks.

For RT320 without the recycler the NOx emissions increased with oil age in general. There was a decrease at around 1,100 miles of oil age, which was associated with a peak in CO and HC emissions that could be due to incomplete combustion in cylinder. Afterwards there was a peak for NOx emissions followed by a decrease. The general trend was illustrated by a linear trendline and the gradient was 15 ppm/kilomile. After the recycler was fitted, the NOx emissions were stabilised and the increase of NOx with oil age was 5 ppm/kilomile. The reduction in the rate of increase of NOx emissions by the recycler was 67%.

For RT321, with the recycler the NOx emissions showed a fluctuated variation with oil age. There was a large peak at around 2,500-3,000 miles of oil age. However, it can be found that a similar peak appeared on the RT320 test at a similar oil age. This similarity indicated that this peak could be caused by deposit accumulation. The peak value, however, lasted longer without the recycler on the RT320 than that with the recycler on the RT321 and the decline in NOx after the peak was larger on the RT321 with the recycler, which suggested that the recycler had removed more deposits from the cylinder and thus led to a more significant decrease in NOx emissions.

The NOx emissions after the recycler had been taken off from the RT321 were showing an increasing trend, although there were some variations. The rate of increase in NOx was 3 ppm/kilomile with the recycler and 22 ppm/kilomile without the recycler. However, the data with the recycler was quite scattered.

Fig.2a RT320

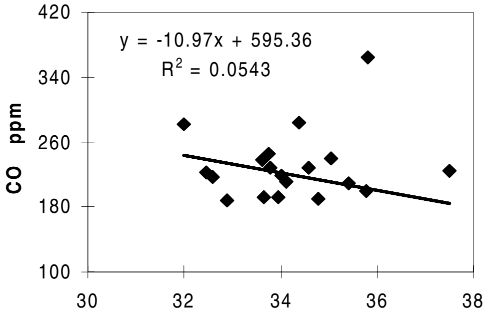


Fig.2b RT320

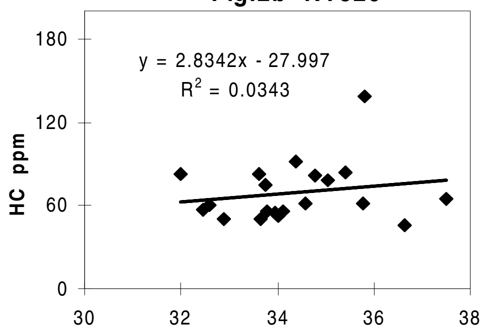


Fig.2c RT320

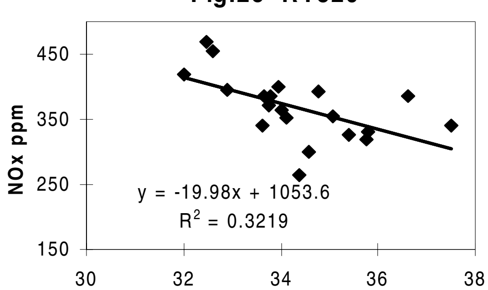


Fig.2d RT320

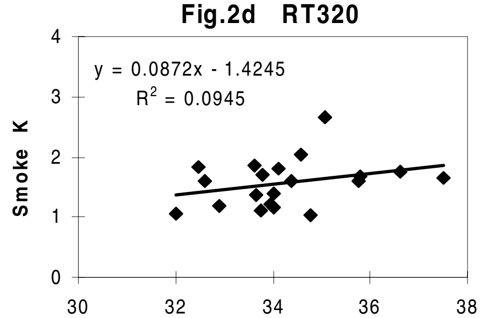


Fig.7.2e RT320

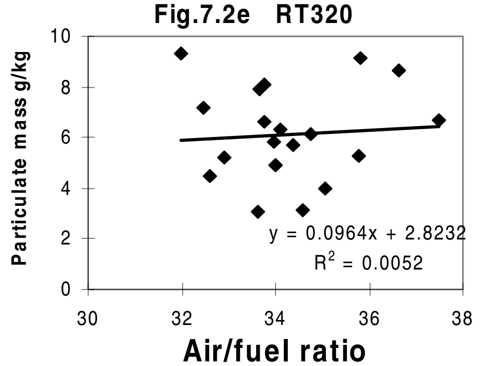


Fig.3a RT321

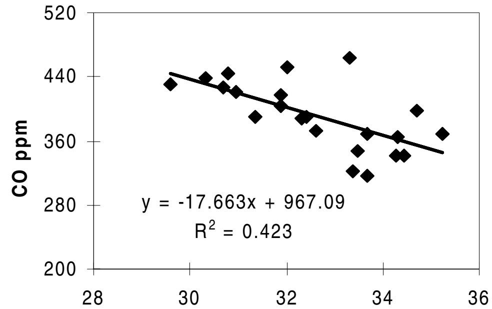


Fig.3b RT321

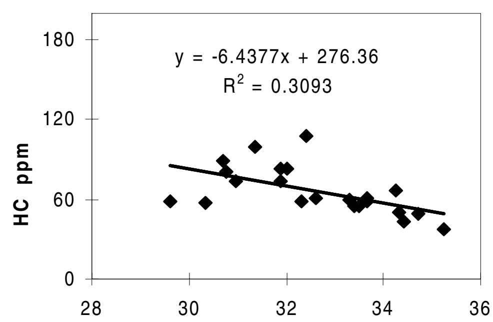


Fig.3c RT321

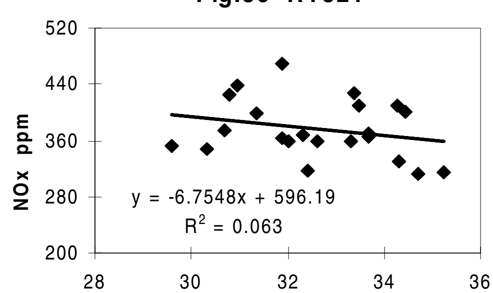


Fig.3d RT321

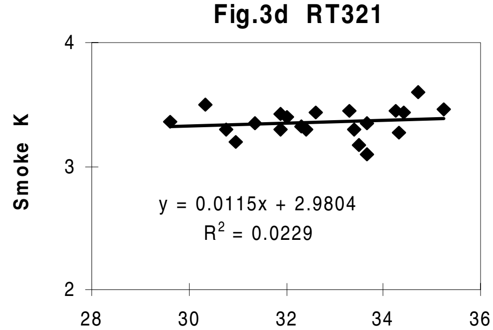


Fig.3e RT321

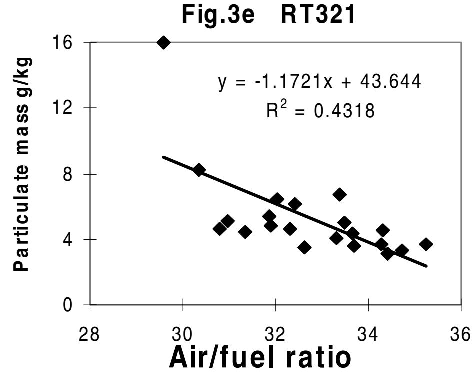


Fig.2f RT320

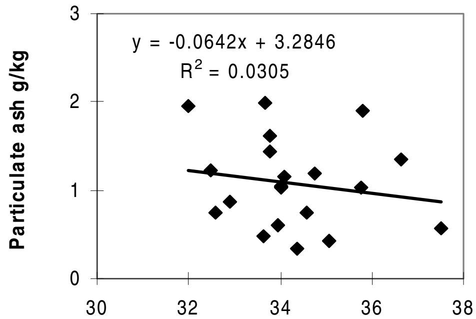


Fig.3f RT321

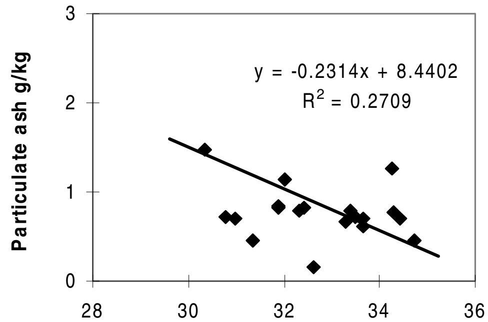


Fig.2g RT320

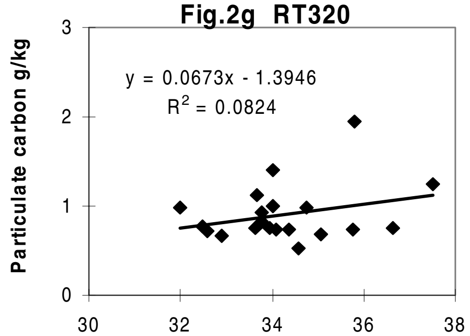


Fig.3g RT321

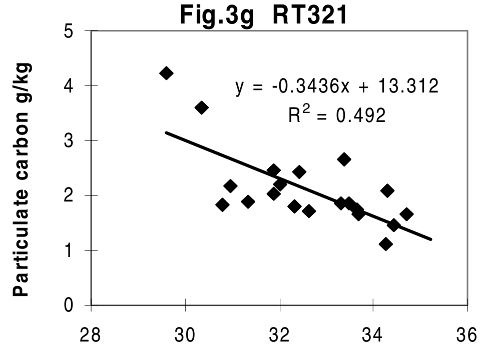


Fig.2h RT320

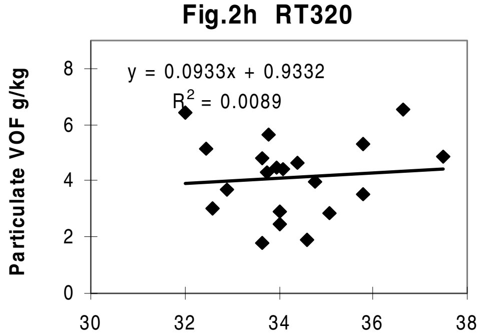


Fig.3h RT321

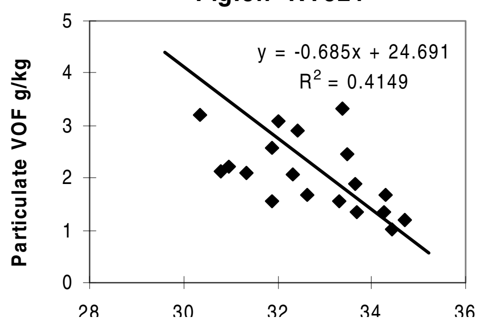


Fig.2i RT320

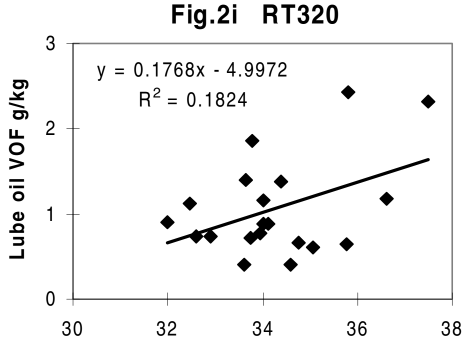


Fig.3i RT321

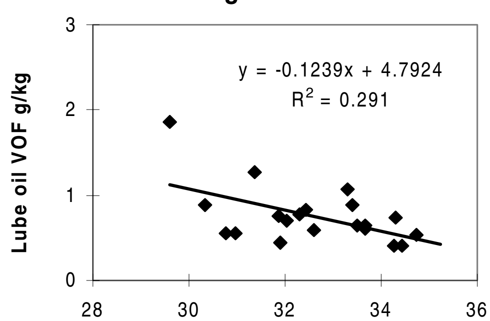
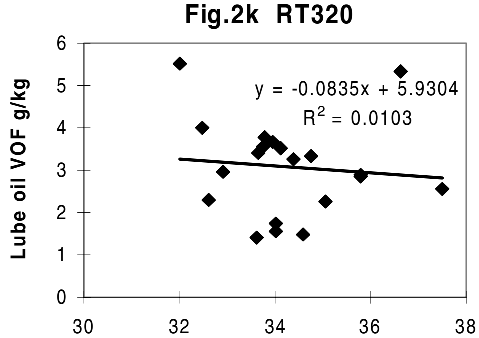
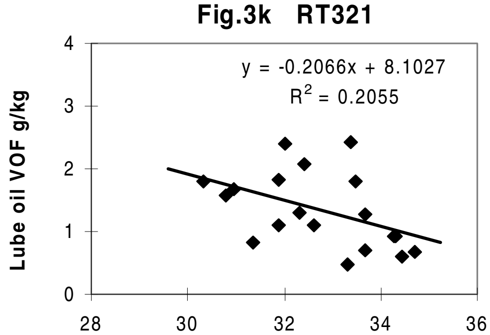


Fig.2k RT320



Air/fuel ratio

Fig.3k RT321



Air/fuel ratio

Fig.4 CO emissions Vs oil age for RT320

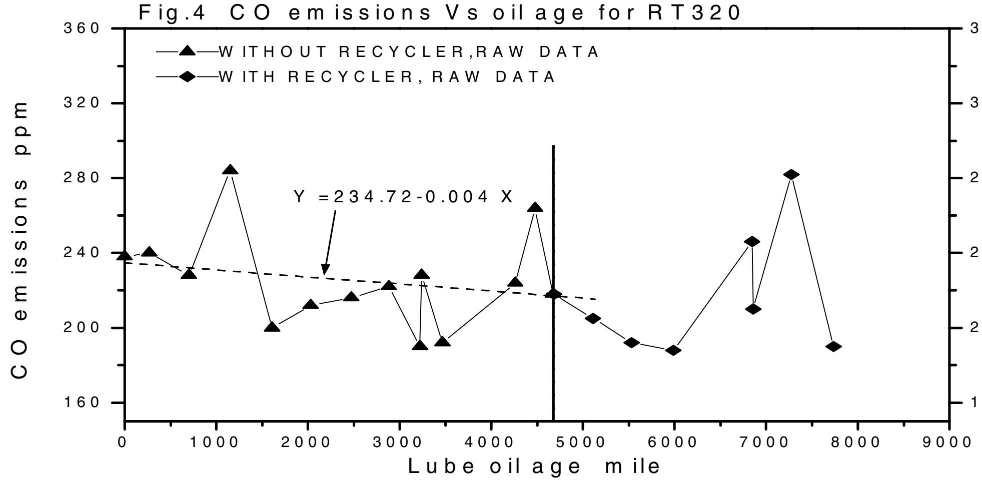


Fig.5 CO emissions Vs oil age for RT321

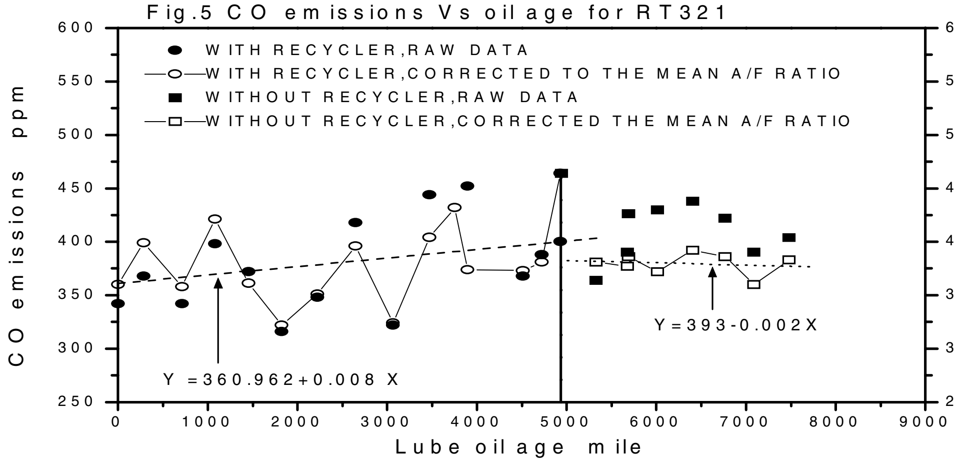
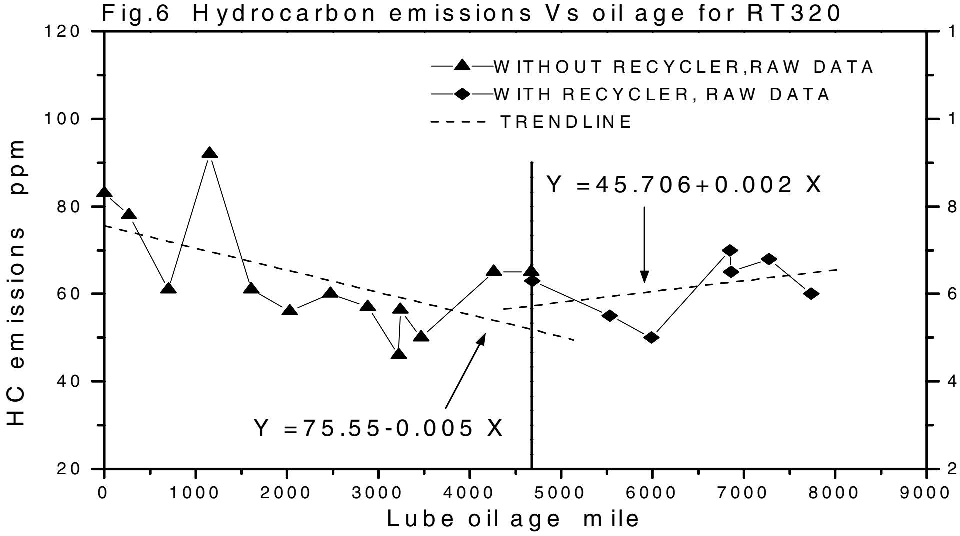


Fig.6 Hydrocarbon emissions Vs oil age for RT320



BLACK SMOKE

Black smokes were not sensitive to the air/fuel ratio within the range of tests as shown in Figs.2d and 3d. The R^2 was 0.09 and 0.02 for two refuse trucks respectively. So the raw data was used to show smoke variation with oil age.

Figs.10 and 11 show the black smoke varied as a function of oil age for two refuse trucks. For RT320 without the recycler, a sharp peak appeared at 270 miles of oil age, which was attributed to the traffic condition. Except this data, the smoke fluctuated around an average value of 1.7 K until 3,500 miles of oil age, where the smoke started to increase continuously. The average value for smoke during 4,700 miles of testing without the recycler for RT320 was 1.7 K. After the recycler was fitted, the smoke was sharply reduced from 1.9 K down to 1.4 K, 8 miles of running with the recycler fitted. Afterwards the smoke showed a gradually declined trend with oil age. The average level of black smoke was 1.2 K with the recycler fitted. Hence a reduction of 0.5 K was achieved by the recycler, which was a 30% reduction.

Refuse truck RT321 showed very high black smoke, twice as high as that on the RT320. The use of the oil recycler had shown an effect on reducing the smoke gradually with oil age. The smoke was about 3.5 k for fresh oil and declined to 3.2 k after nearly 5,000 miles of oil age. After the recycler had been taken off the smoke increased from 3.2 k to 3.5 k just after 8 miles of travel. Then the smoke decreased and increased periodically around an average value of 3.4 K. Thus the reduction in smoke by the recycler could be worked out by comparing the smoke just before and after taking off of the recycler. This was 0.3 K.

In sum, the recycler has shown an apparent improvement on the reduction of black smoke. The reduction on smoke for RT320 was 30% and 9% for RT321. The less improvement for RT321 was due to very high smoke for baseline test. With the recycler fitted the smoke decreased with oil age for both trucks whereas the baseline tests for both trucks showed a constant level with some fluctuations. The recycler reduced the smoke very rapidly after its fitting and the smoke deteriorated in a very short period when the recycler was taken off.

PARTICULATE EMISSIONS

TOTAL PARTICULATE EMISSIONS - It has been shown in Figs.2e and 3e that the total particulate emissions were sensitive to the air/fuel ratio only for RT321. Therefore the raw data was plotted against the oil age for RT320 as shown in Fig.12 The raw and air/fuel ratio corrected total particulate mass was plotted against the oil age for RT321 as shown in Fig.13.

For RT320, without the recycler the total particulate emissions increased with the oil age with a series of increases and decreases. The mass of total particulates increased from 3 g/kgfuel of fresh oil to 9 g/kgfuel after 4,700 miles of oil age. The average rate of increase in total particulate emissions was 1 g/kgfuel per kilomile. After the recycler was fitted to RT320, the particulate mass was reduced by 46% immediately followed by slow increases with oil age. There was a peak at about 7,300 miles of oil age or 2,600 miles after the recycler was fitted, where the total particulate mass was increased by about 3 g/kg or 35%. This peak was associated with an increase in particulate ash and VOF discussed later. During the testing period with the recycler fitted, the rate of increase in total particulate mass was 0.5 g/kg per kilomile on average, excluding the peak point. Thus the reduction of increase rate in particulate mass by the recycler was 0.5 g/kg per kilomile or 50% for RT320.

The total particulate emissions were showing an increasing trend with a series of increases and decreases with oil ageing on the RT321 test with the recycler. The average rate of increase in particulate mass was 0.4 g/kg per kilomile. After the recycler was taken off, there was a huge peak at 6,000 miles of oil age, where the mass of particulates reached 16 g/kg and was about three times higher than average level. It is noted that this peak in particulate mass was following the peak in hydrocarbons (appeared at 5,700 miles). This could be explained that certain amount of hydrocarbons from lube oil stored in the cylinder due to incomplete combustion could gave rise to a peak in hydrocarbon emissions. Then these lube oils were burned and resulted in an increase in total particulate emissions. It will be shown later that the particulate ash, carbon and VOF emissions increased at the same time, which indicated the excessive lube oil was burned. As the excessive lube oil was burnt, more ash would be produced and some went into particulates and some would went into the oil. Thus there would be an increase in additive metals in the oil. The oil analysis proved this when the calcium and zinc in oil reached a peak.

PARTICULATE ASH EMISSIONS - There was no good correlation between particulate ash emissions and air/fuel ratio. Therefore the raw data was used to show the particulate ash emissions as a function of oil age in Figs.14 and 15.

Without the recycler RT320 showed an apparently increasing trend in particulate ash emissions with oil age. The rate of increase in particulate ash mass was 0.2 g/kg per kilomile. After fitting the oil recycler the mass of the particulate ash decreased very quickly and remarkably. The fall in the mass of particulate ash before and after the fitting of the recycler was from 1.91 g/kg down to 1.06 g/kg. i.e. 45% of instant reduction by the recycler.

Fig.7 Hydrocarbon emissions Vs oil age for RT321

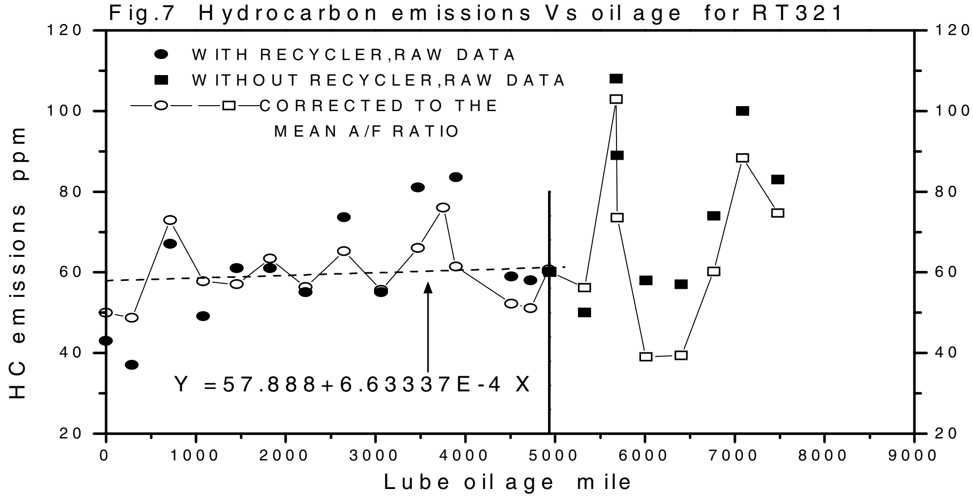


Fig.8 NOx emissions Vs oil age for RT320

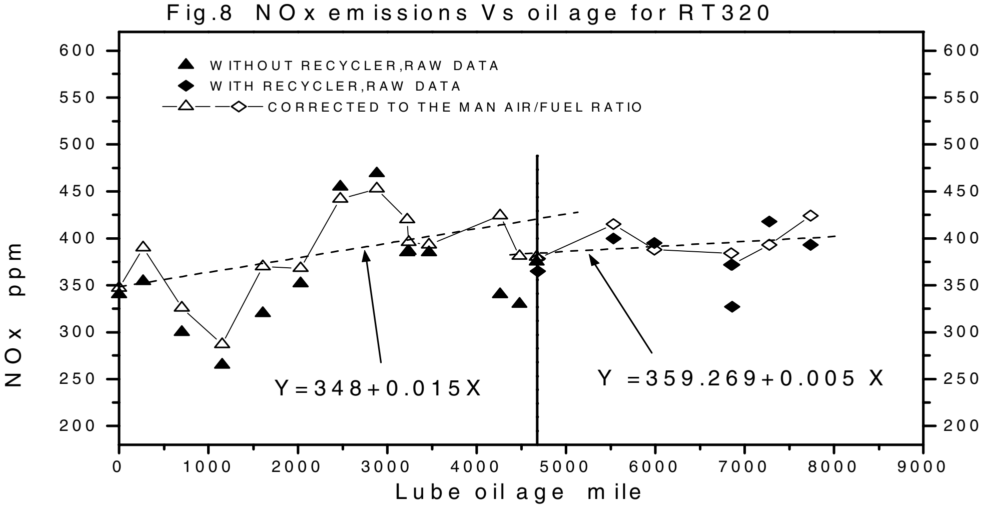


Fig.9 NOx emissions Vs oil age for RT321

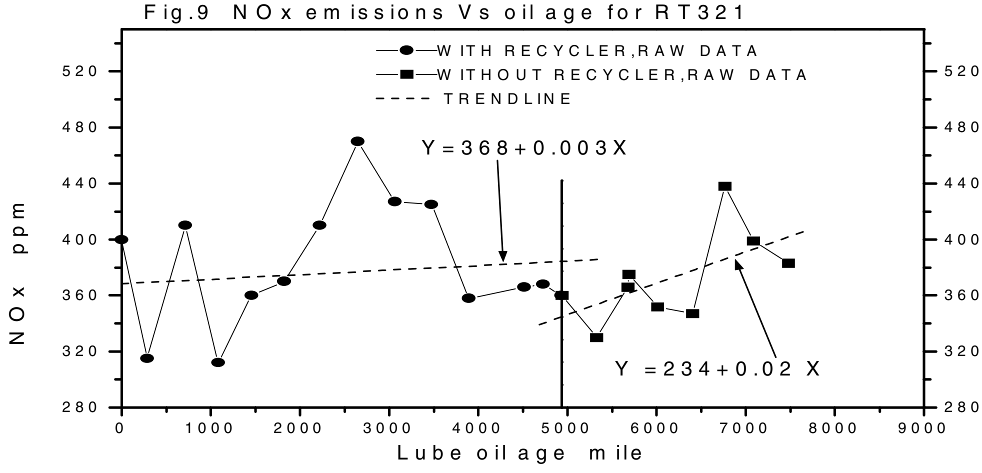


Fig.10 Black smoke Vs oil age for RT320

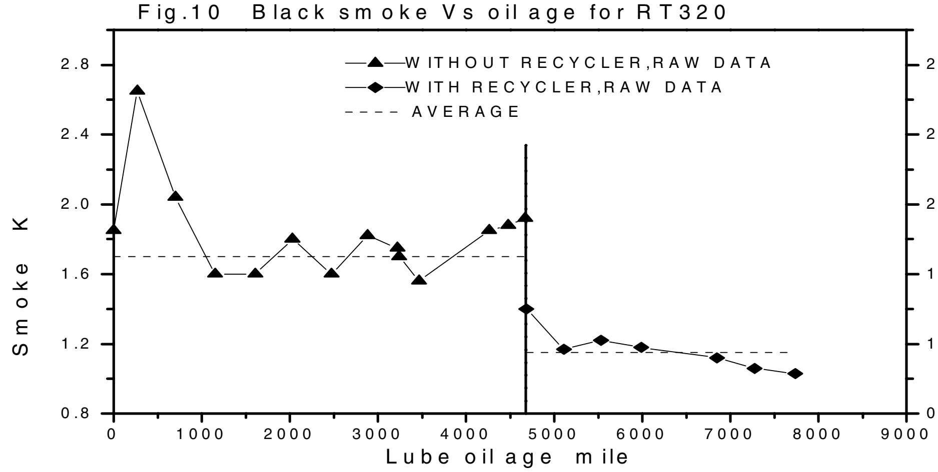


Fig.11 Black smoke Vs oil age for RT321

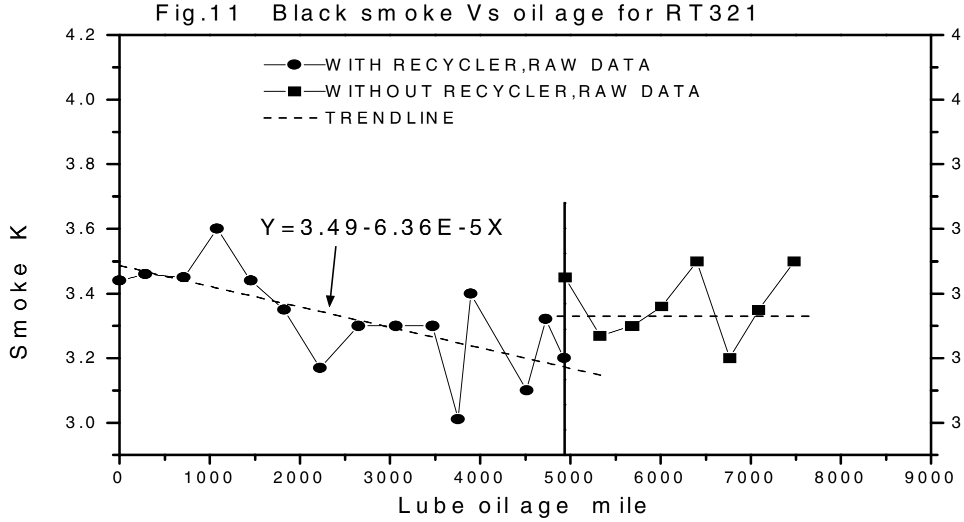
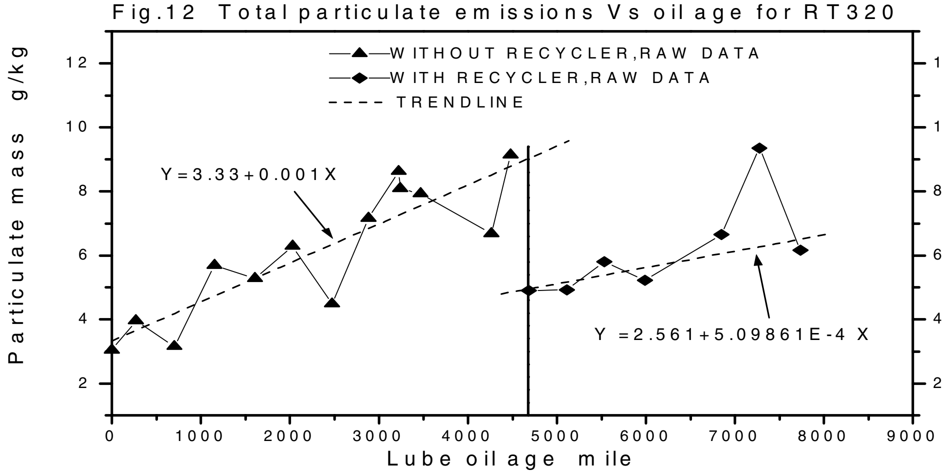


Fig.12 Total particulate emissions Vs oil age for RT320



This reduction in particulate ash mass suggested that the recycler reduced the lube oil consumption. The particulate ash then had a decrease after 800 miles with the recycler fitted and from here started to increase continuously until it reached a peak at 7,300 miles. This peak was associated with the increase in total particulate emissions. The general trend in particulate ash with the recycler was a slightly increasing trend.

For RT321, with the recycler the particulate ash was firstly increased and then decreased in the first 1,900 miles of oil age. Afterwards it was stabilised except for a small peak at 4,000 miles. The average level for particulate ash emissions was 0.75 g/kg with the recycler. After taking off of the recycler, the particulate ash had a large peak at 6,000 miles, where the mass of particulate ash was over four times higher than average level and this peak was associated with the peak in total particulate emissions. Except this peak, there was no significant difference in particulate ash emissions before and after the fitting of the oil recycler on RT321 test.

PARTICULATE CARBON EMISSIONS - There was no correlation between air/fuel ratio and particulate carbon emissions for RT320 and yet the correlation existed for RT321 as shown in Figs.2g and 3g. The raw and air/fuel ratio corrected data was demonstrated in Figs.16 and 17.

For RT320 without the recycler fitted, the particulate carbon had an initial decrease in the first 700 miles and then stabilised in the next 2000 miles. There was a remarkable increase in particulate carbons in the last 1,500 miles, which was corresponding to the increasing trend in black smoke. After the recycler was fitted, the mass of particulate carbon decreased immediately and continued to decrease for another 1,300 miles, followed by a small increase to 1.0 g/kg and then stabilised.

For RT321 with the recycler, particulate carbon emissions were showing a constant trend fluctuated around a mean value of 1.75 g/kg. After the recycler was taken off, the particulate carbon started to increase and reached a peak with a doubled value at the oil age of 6,000 miles, followed by a fall back to the average level. This huge peak was associated with the total particulate and particulate ash peaks.

The level of particulate carbon emissions for RT321 was doubled, compared to the results for RT320. This was co-ordinated with the black smoke emissions discussed earlier, which showed the smoke for RT321 was twice as high as for RT320.

PARTICULATE VOF EMISSIONS - Particulate VOF (Volatile Organic Fractions) was determined by the TGA technique and had a good correlation with the air/fuel ratio for RT321 (R^2=0.41), but no correlation for RT320(R^2=0.01) as shown in Fig.2h and 3h. Thus the raw data of particulate VOF was plotted against oil age for RT320, and the raw and air/fuel ratio corrected data of particulate VOF was plotted against oil age for RT321 as shown in Figs.18 and 19.

For RT320 without the recycler the particulate VOF emissions fluctuated periodically. Its variation was corresponding to that of total particulate mass. The general trend was an increasing tendency. The gradient for increase in particulate VOF was 0.78 g/kg per kilomile. After the fitting of the recycler, the particulate VOF mass was reduced by 55% immediately. there was a significant peak at 7,300 miles of oil age and a small peak at 5,500 miles. These two peaks were corresponding to the total particulate emission peaks at the same time. The general trend in particulate VOF emissions was increasing with the oil ageing and the average rate of increase was 0.77 g/kg per kilomile. Hence the rate of increase in particulate VOF emissions was not changed by the recycler.

For RT321 with the recycler, the particulate VOF mass increased slowly with less variation compared to that for RT320. There was a huge peak at 6,000 miles of oil age where the recycler had been taken off. This peak also appeared in particulate ash and carbon emissions as discussed above. it is postulated that this peak was due to mis-function of the engine.

These two refuse trucks behaved quite differently in particulate VOF emissions. For RT321 the particulate VOF mass was less oil age dependent, compared to that for RT320. The overall particulate VOF emissions for RT321 was much lower than that for RT320.

LUBE OIL VOF EMISSIONS - The particulate lube oil VOF emissions appeared correlated to the air/fuel ratio only for RT321, shown in Figs.2i and 3i. Figs.20 and 21 show the raw and corrected data for two trucks.

For RT320, without the recycler the particulate lube oil VOF emissions showed an increasing trend from 0.5 g/kg of fresh oil to 2.5 g/kg after 4,700 miles. The average rate of increase was 0.35 g/kg per kilomile. There was a peak at 1,100 miles of oil age, where CO, hydrocarbons, smoke were also showing a peak. This indicated that the temperature in combustion chamber was low for some reason so that more incomplete combustion products were produced. After the recycler was fitted, there was an immediate decrease in lube oil VOF emissions and the trend was showing a continuous decrease with oil age. The fall in lube oil VOF by the recycler was 65% by mass.

Fig.13 Total particulate emissions Vs oil age for RT321

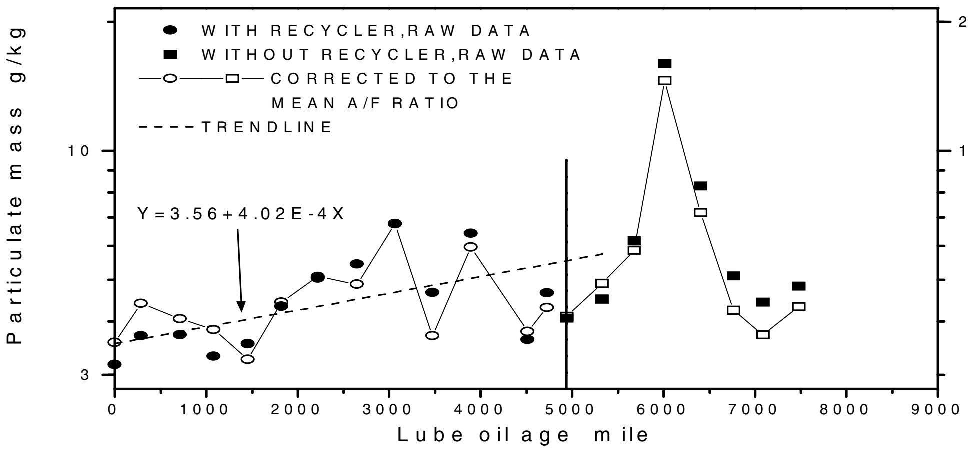


Fig.14 Particulate ash Vs oil age for RT320

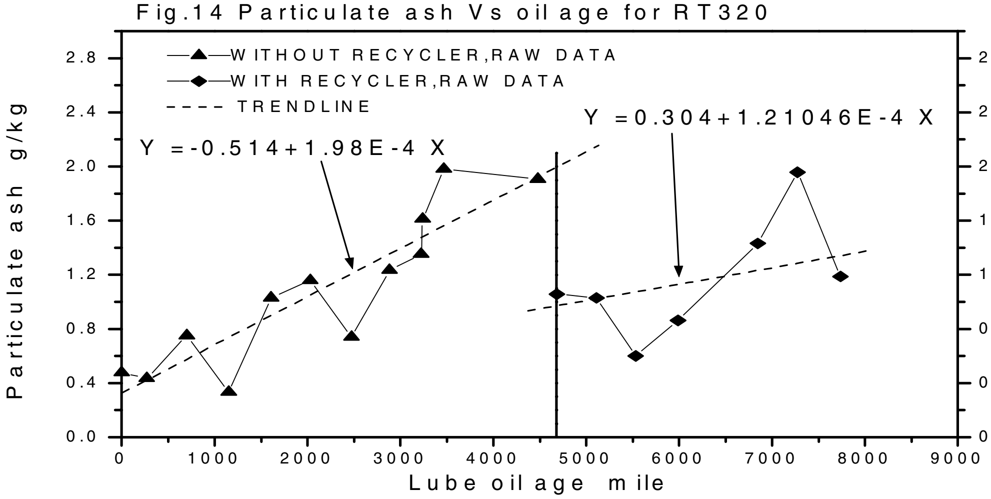
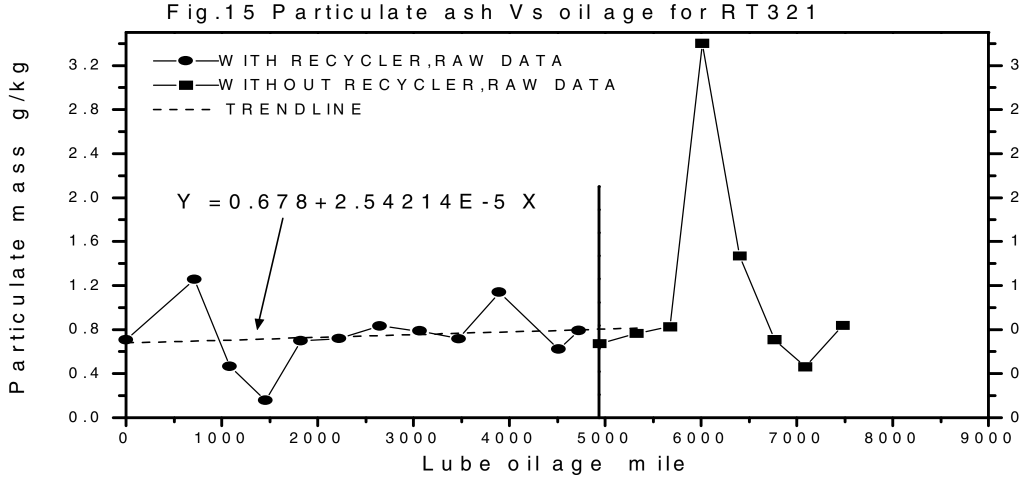


Fig.15 Particulate ash Vs oil age for RT321



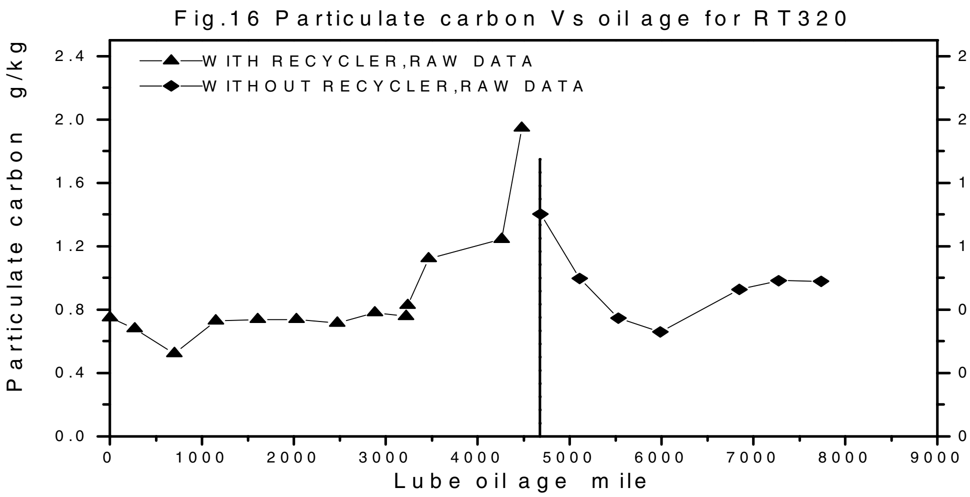


Fig.16 Particulate carbon Vs oil age for RT320
WITH RECYCLER,RAW DATA
WITHOUT RECYCLER,RAW DATA
Particulate carbon g/kg
Lube oil age mile

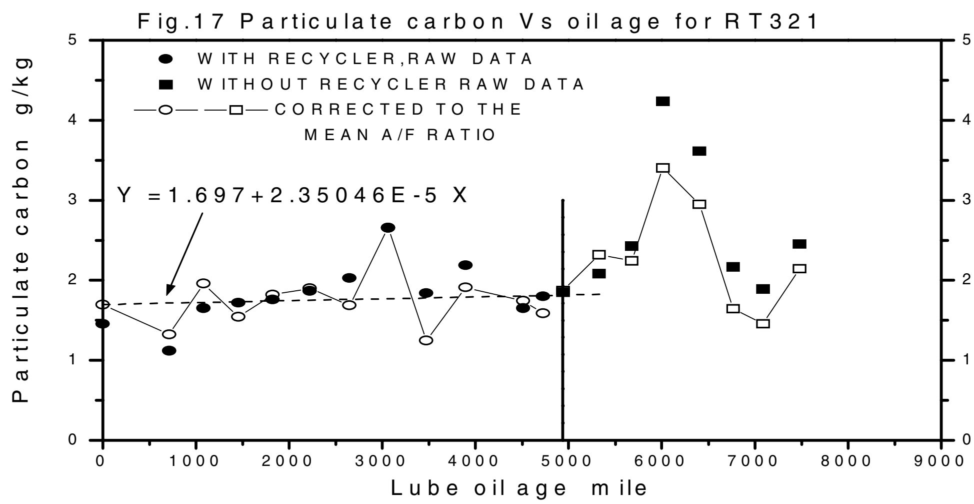


Fig.17 Particulate carbon Vs oil age for RT321
WITH RECYCLER,RAW DATA
WITHOUT RECYCLER RAW DATA
CORRECTED TO THE
MEAN A/F RATIO
Y =1.697+2.35046E-5 X
Particulate carbon g/kg
Lube oil age mile

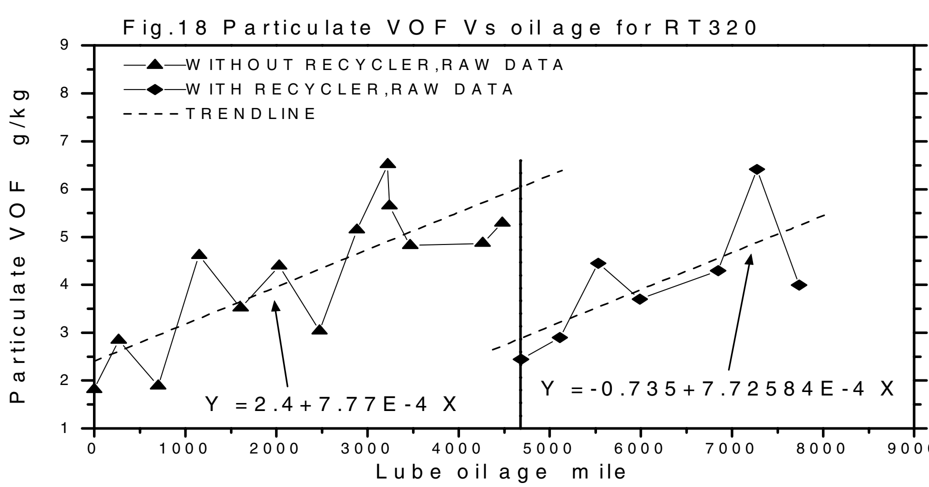


Fig.18 Particulate VOF Vs oil age for RT320
WITHOUT RECYCLER,RAW DATA
WITH RECYCLER,RAW DATA
TRENDLINE
Y =2.4+7.77E-4 X
Y =-0.735+7.72584E-4 X
Particulate VOF g/kg
Lube oil age mile

Fig.19 Particulate VOF Vs oil age for RT321

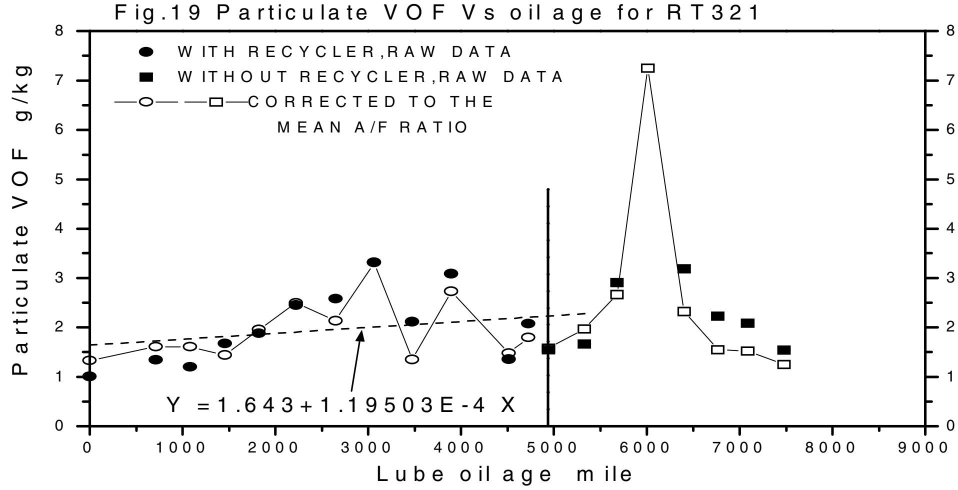


Fig.20 Lube oil VOF emissions Vs oil age for RT320

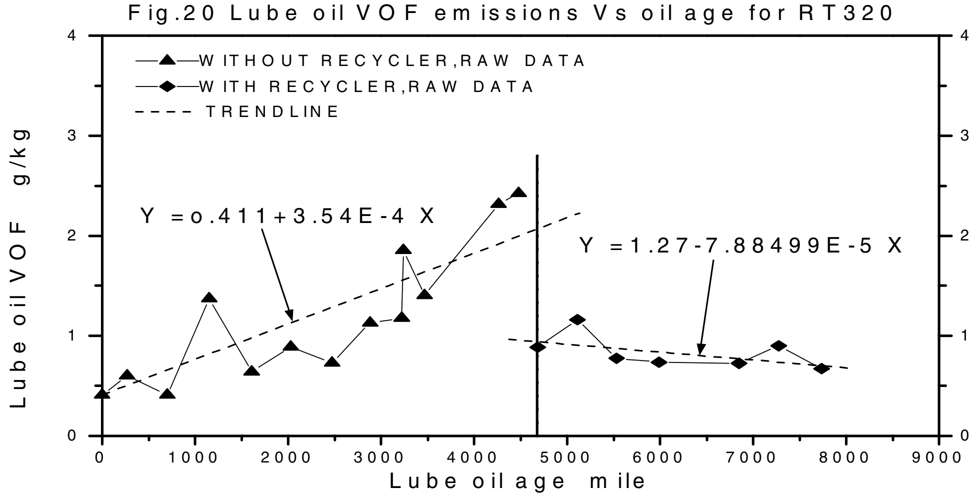


Fig.21 Lube oil VOF emissions Vs oil age for RT321

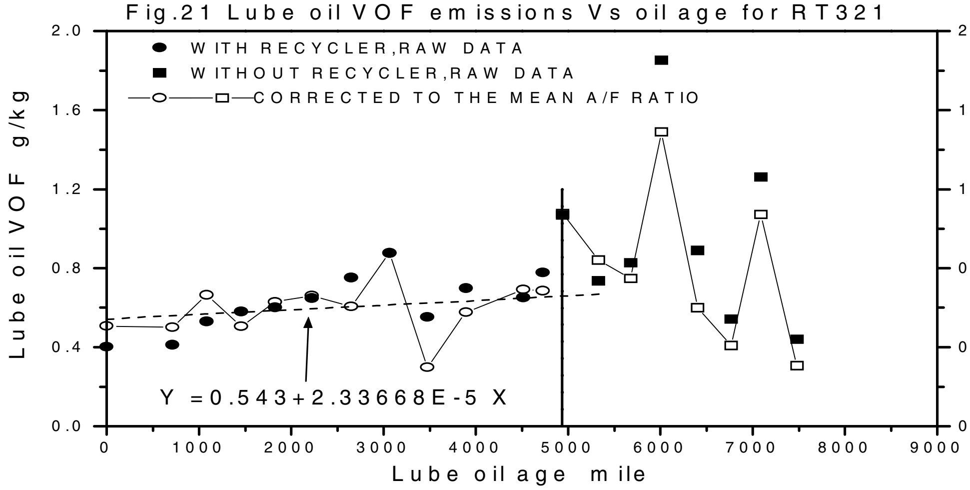


Fig.22 Fraction of lube oil VOF to total VOF emissions for RT320

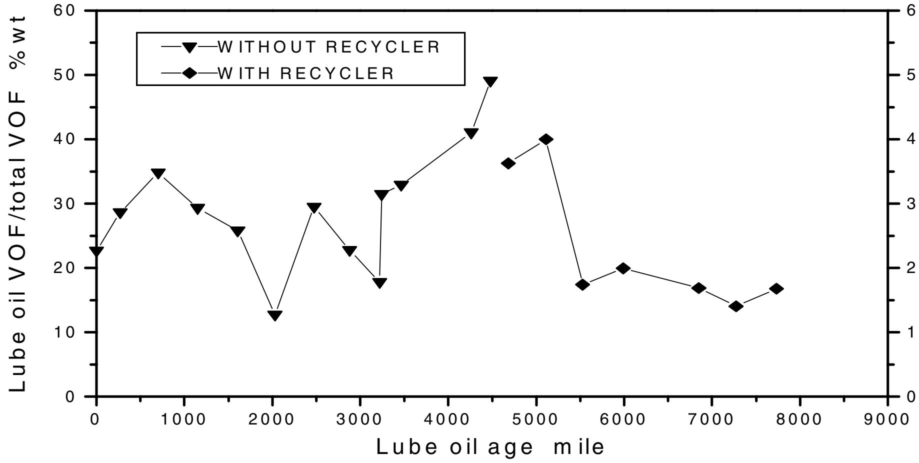


Fig.23 Fraction of lube oil VOF to total VOF emissions Vs oil age for RT321

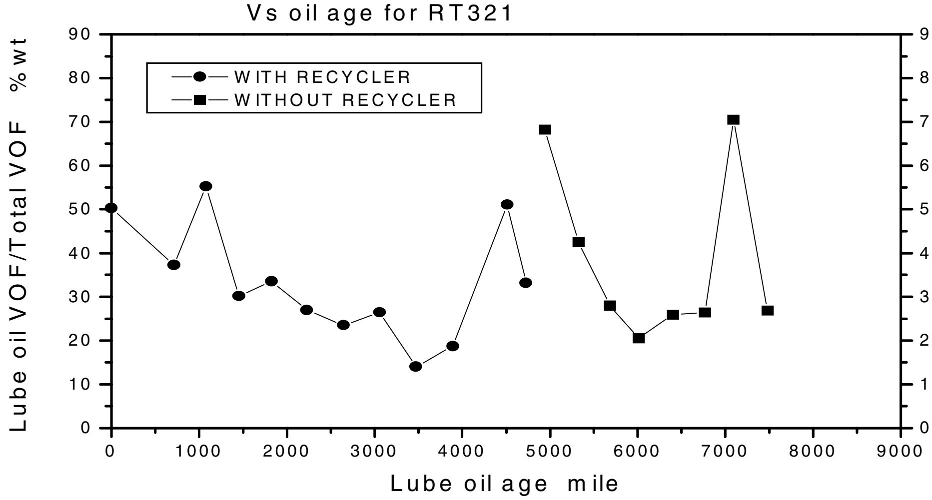
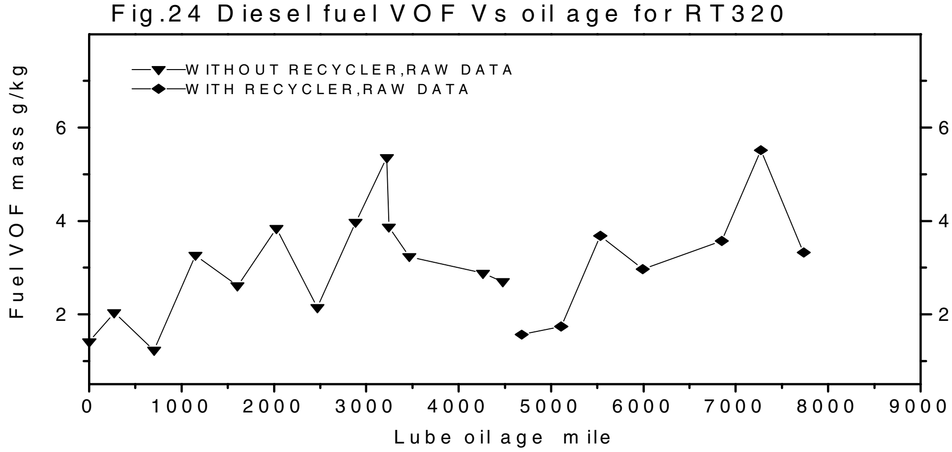


Fig.24 Diesel fuel VOF Vs oil age for RT320



For RT321, with the recycler fitted the lube oil VOF was showing a slightly increasing trend around 0.6 g/kg. After the recycler was taken off, there was an immediate increase (43%) in lube oil VOF mass emissions followed by decreasing trend. A large peak appeared at 6,000 miles, which was associated with the peaks in particulate ash and carbon emissions. Differing from other emission parameters, there was a second peak at 7,000 miles, which was only appeared for lube oil VOF. This indicated there were lube oil remains in the combustion chamber, possibly due to absorption of lube oil on deposits. The deposits were increased after the taking off of the recycler, which was proved by the NOx emission rise in Fig.7.49. Thus more lube oils could be absorbed and then released.

Figs.22 and 23 illustrated the lube oil VOF as a percentage of total particulate VOF for two refuse trucks. For RT320 without the recycler the lube oil VOF took up about 20-35% of total VOF. The fraction of lube oil VOF had a 10% drop after the recycler was fitted and further decreased to 15 to 20% after 800 miles of operation of the recycler. For RT321, with the recycler the fraction of lube oil VOF decreased continuously from fresh oil till 4,000 miles. With the recycler taken off, the fraction of lube oil VOF immediately increased to 70% and then decreased. A peak appeared at 7,000 miles of oil age where the lube oil VOF rose up to 70%.

UNBURNT FUEL VOF EMISSIONS - There was no good correlation between fuel VOF emissions and air/fuel ration as shown in Fig.2k and 3k. Hence the raw data was presented as a function of oil age.

The diesel VOF showed an increasing trend with oil age for RT320 tests both with and without the recycler. Similarly, there was an immediate decrease in diesel VOF mass after the fitting of the recycler. The diesel VOF was relatively stable for RT321 tests, except a huge peak appeared at the oil age of 6,00 miles. The diesel VOF mass was higher for RT320 than that for RT321. The details were shown in Figs.24 and 25.

COMPOSITION OF PARTICULATE EMISSIONS - Particulate mass emissions were analysed for particulate ash, carbon, total VOF, lube oil VOF and fuel VOF emission as shown above. All these components of particulates were integrated into a single plot to see the composition of the particulate emissions as a function of oil age as shown in Figs.26 and 27.

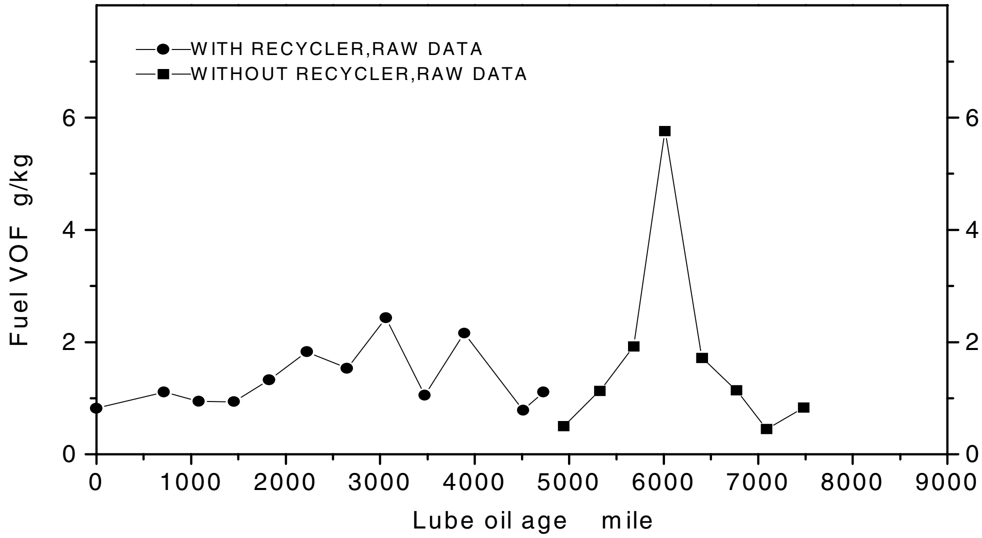
It has shown that for RT320 the variation of total particulate mass with oil age was primarily depending on the total VOF mass variation and secondarily on the ash mass variation. The variation of particulate carbon mass was independent to total particulate mass. The variation of total VOF mass was mainly decided by the fuel VOF mass variation. Similarly for 321, the variation of total particulate mass with oil age was primarily depending on the total VOF mass variation and yet secondarily depending on both ash and carbon mass variation. The VOF emissions was mainly affected by the fuel VOF variation. A huge peak at 6,000 miles appeared at all phases of particulate emissions.

The composition analysis were showing that for RT320, the particulate VOF took up 60-80% of total particulate emissions. The particulate ash varied from 10-30% and carbon varied from 10-20% of total particulate mass. Among the total VOF fraction, the fuel VOF contributed 40-60% to total particulate mass and lube oil VOF had a contribution of 10-20 % to total particulate mass. The fitting of an oil recycler on RT320 initially reduced total VOF fraction due to a reduction of lube oil VOF fraction but increased ash fraction and at late stage the ash fraction was reduced and the VOF fraction was recovered to the level of without the recycler. The recycler had reduced lube oil contributions to total particulate mass in terms of percentage.

For RT321, a high carbon contribution of 30-50% to total particulate emissions was revealed. The ash fractions were between 10-20%. The total VOF fractions were about 40-50%. Compared to the results from RT320, particulate emissions for RT321 revealed a higher carbon, lower total VOF, lower fuel VOF and similar ash fractions. The high carbon emissions resulted in high black smoke. The taking off of the recycler from the RT321 led to an increase in the fractions of particulate carbon.

PYROLYSIS GAS CHROMTOGRAPHY OF PARTICULATES - The pyro-probe GC was used to analyse the particulate samples to show the carbon number distribution of particulate VOF fractions. Fig.28 shows the profiles of particulates with and without the recycler for RT320. Fig.29 shows the results for RT321 test. It clearly shows that fuel peaks ranging from C13-C26 and lube oil peaks ranging from C20 upwards existed for two refuse trucks. For RT320, without the recycler it shows more lube oil fractions ranging around C27 and slightly less fuel fractions ranging from C13-C15 existed, compared to the profile with the recycler. For RT321, without the recycler the slightly more fuel fractions ranging from C13-C15 and slightly more lube oil fractions appeared, compared to the results with the recycler .

Fig.25 Diesel fuel VOF Vs oil age for RT321



CONCLUSIONS

Two refuse trucks with a similar age were selected and the tests were carried out to evaluate the influence of the TOP-HIGH lube oil recycler on emissions and lube oil quality as well as lube oil and fuel consumption. The two refuse trucks were 1991 model fitted with Perkins Phazer 210Ti series turbocharger intercooled engines with EURO-I emission compliance. These two refuse trucks carried out similar duties and used the same mineral lube oils and low sulphur diesel fuels. The lube oil and emissions samples were taken every two weeks or 400 miles on average and analysed. The results are showing that with the recycler:

There is no improvement on carbon monoxide emissions.

NOx emissions varied with oil age. The recycler reduced the rate of increase in NOx emissions.

No notable effect on gaseous hydrocarbon emissions.

The recycler shows a significant reduction on black smoke, not only the absolute value but the rate of increase. With the fitting of a 1 micron pore size filter recycler, the black smoke decreased by 30%.

The increase rate of total particulate emissions has been reduced by 50%. An immediate 46% decrease in particulate mass has been observed after fitting the recycler.

Particulate ash emissions were reduced by 50%. The rate of increase in particulate ash has been slowed down by 40%.

Particulate carbon emissions were reduced. The RT321 had a doubled particulate carbon emissions and thus doubled black smoke, compared to the results for RT320.

A reduction of 55% in particulate total VOF emissions has been achieved .

The lube oil VOF emissions were reduced by 30-65%.

The RT320 had higher VOF emissions whereas the RT321 had higher carbon emissions and thus higher black smoke emissions.

The 1 micron pore size filter in the recycler has shown a higher efficiency on improving oil quality and consequently reducing the emissions than 6 micron size filter.

ACKNOWLEDGEMENTS

We would like to thank Top High UK for a research scholarship to Hu Li and for a research contract. We would like to thank Manchester City Council, Gorton Depot for their co-operation in this work and in particular to John Stanway, General Manager and Joe Stephens, Works Manager. The technical assistance was given by Ian Langstaff and Geoff Cole.

Fig.26 Composition of the particulate emissions Vs oil age for RT320

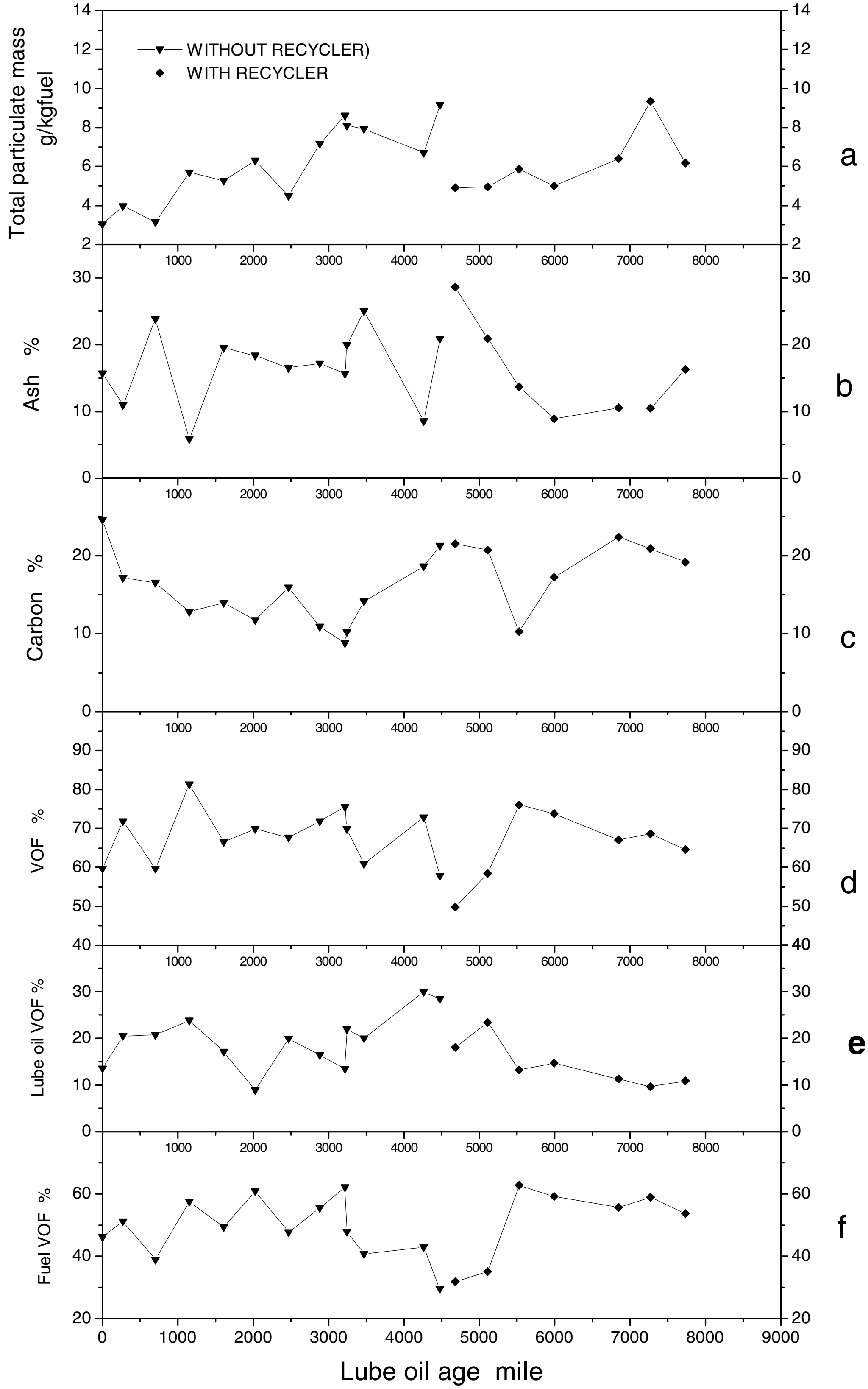
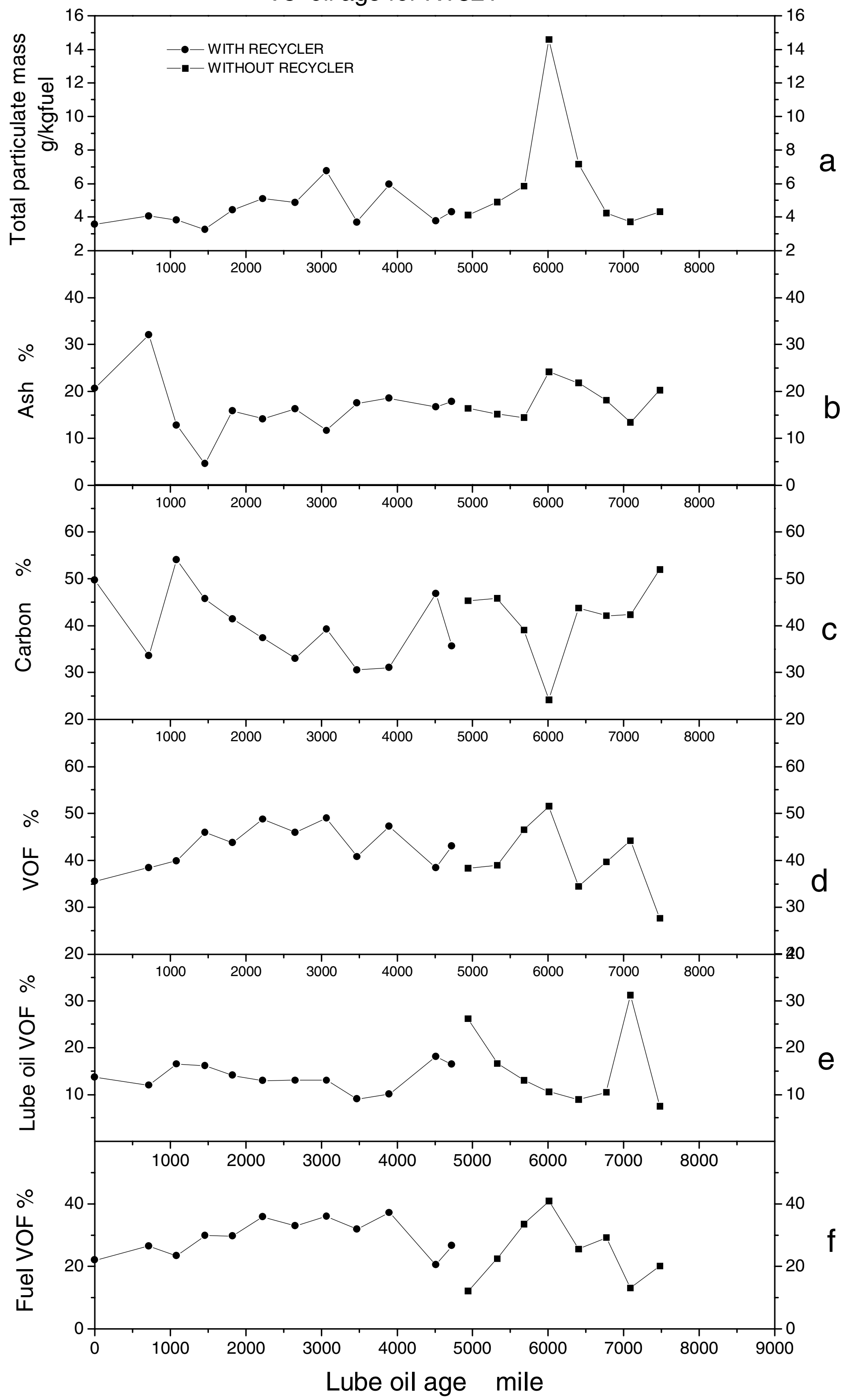


Fig.27 Composition of the particulate emissions
Vs oil age for RT321



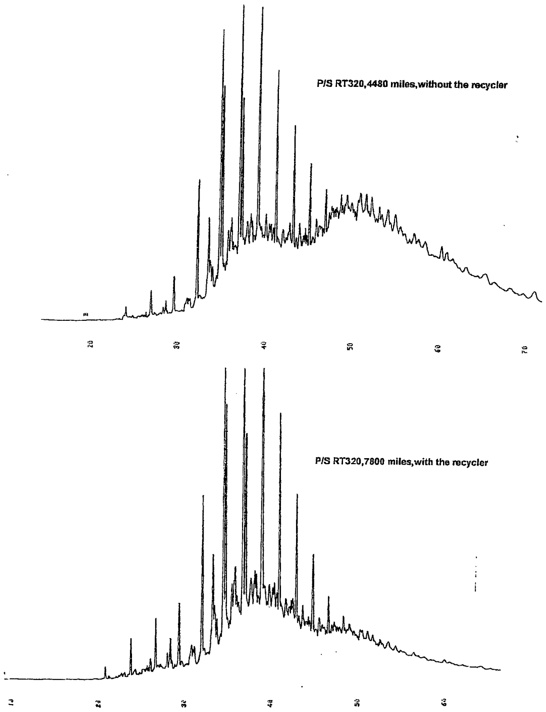


Fig. 28 Pyro-probe GC of particulates for RT 320

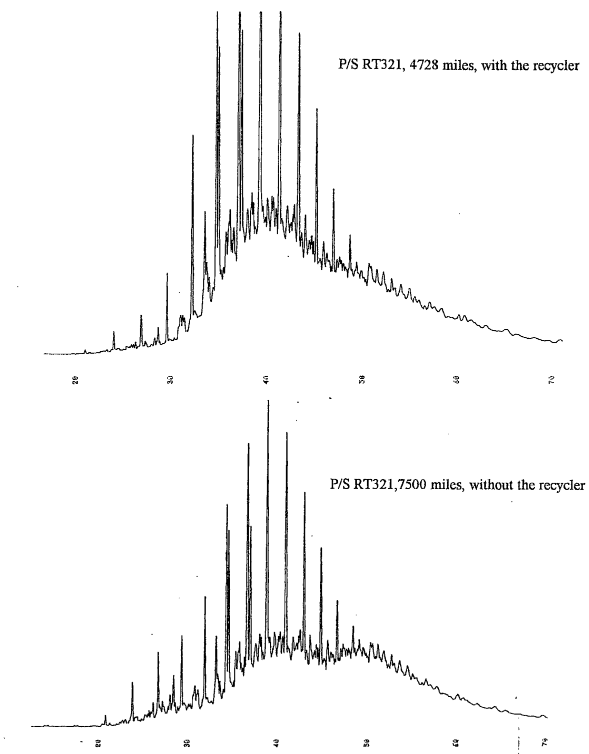


Fig. 29 Pyro-probe GC of particulates for RT 321

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