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# Particulates Reduction in Diesel Engines Through the Combination of a Particulate Filter and Fuel Additive

**M W Vincent, P Richards and S L Cook**
The Associated Octel Company Limited

## ABSTRACT

Exhaust emissions legislation for diesel engines generally limits only the mass of emitted particulate matter. This limitation reflects the concerns and measurement technology at the time the legislation was drafted. However, evolving diesel particulate filter (DPF) systems offer the potential for reductions in the mass and more importantly, the number of particles emitted from diesel exhausts.

Particulate filters require frequent cleaning or regeneration of accumulated soot, if the engine is to continue to operate satisfactorily. Exothermic reactions during regeneration can lead to severe thermal gradients in the filter system resulting in damage. Fuel additives have been evaluated to show significant reductions in light off temperature which allow frequent small regeneration events to occur, under mild operating conditions. The resulting small exotherms suggest that low back pressure filter systems giving frequent regenerations could in the future become as reliable in use as gasoline exhaust catalyst systems.

## INTRODUCTION

Since the inception of the diesel engine, in 1892, the combustion process in such engines has involved the oxidation of carbon-based particles. In Rudolf Diesel’s patent (1), the fuel was pulverised coal. In the modern diesel engine the fuel is liquid hydrocarbon which via processes such as pyrolysis, polymerisation, hydrogen abstraction, etc. (2-4) is converted to carbon particles (plus other products such as hydrogen, chemi-ions, water, etc.). Unfortunately, these carbon-based particles are not all fully oxidised by the time the exhaust valve opens, and consequently some carbon particles are emitted along with the exhaust gases. These carbon-based particles will also carry adsorbed hydrocarbons and other combustion products such as sulphates, nitrates, etc., and are commonly referred to simply as “particulates”. The larger particulates are observed as “black smoke” and are a contributory factor in the fouling of buildings in areas of heavy traffic. Smaller particulates, usually invisible to the naked eye, are increasingly linked to health concerns.

Coincidental to the increase in volume of diesel engines has been an increase in environmental awareness. This has resulted in a pressing need to reduce the level of particulate emissions. One way to achieve this is to raise the temperature of the combustion process to promote oxidation. However, this has the disadvantage of increasing the amount of oxides of nitrogen formed. Another approach is to increase the local air to fuel ratio by better mixing of the fuel and air. Here again, however, there is a tendency to increase emissions of oxides of nitrogen. Great advances have been made along this path, but it is still considered that such measures will not be sufficient to meet proposed future legislation.

Fuel additives have also been proposed to inhibit the formation of or to aid the oxidation of particulates (5-8). To date none of these additives has shown an ability to reduce particulates sufficiently to meet proposed future legislation. An attractive alternative, therefore, is to filter out the particulates and dispose of them in an environmentally acceptable way. Many such diesel particulate filter (DPF) systems have been proposed (9-14).

Concern over diesel particulate emissions is now moving from the total mass emitted to the number of particles below a certain size (the size limit is still being debated). Previous work has considered the particle size distribution of diesel emissions and the effect of DPFs upon these distributions (15-17). The effect of alternative DPF technologies has been investigated (18,19). Filtration efficiencies of greater than 90% are typical (17). Recently the joint European project VERT concluded “... several filter systems have been investigated that satisfy the stringent criteria ...” (20).

DPFs would therefore seem to offer a potential solution to the problem. However, trapping particulates causes a secondary problem, namely, the disposal of the trapped particulates. If the correct conditions can be generated then the particulates will oxidise, ie. will be burned off. Unfortunately the correct conditions do not occur naturally with sufficient frequency. Various approaches have been tried to bring about the correct conditions for oxidation; the temperature can be raised using a burner (21) or by electrical heating (22), or a catalyst may be employed either on the DPF (23) or in the fuel (24-28). If the catalyst is applied to the DPF, as soot accumulates it forms a barrier between the catalyst and the oxygen bearing atmosphere, thus significantly reducing the effectiveness of the catalyst. Use of a catalyst in the fuel is thus believed to be the most efficient route, and to this end Octel has been developing fuel additives to aid in the self regeneration of DPFs. Early development work was conducted using a wound ceramic fibre, deep bed (10) type DPF (29-31). From this work it was found that there was a synergistic effect from combining group I and group II metals (32). Alternative DPF materials evaluated include Cordierite, a ceramic material widely employed as an exhaust catalyst substrate. Modifications in the production process enable the material to be employed as a DPF material, which is very effective at trapping the particulate material present in diesel engine exhaust gas.

Although the additive gave the required performance in assisting the self regeneration of the DPF, both on the test bench and in a vehicle on the road, other work has led to reported interaction between the ceramic material and a sodium additive(26, 33). The ceramic material used in these reported instances was Cordierite.

Tests were carried out with both Cordierite and another ceramic DPF material, silicon carbide, using passenger car diesel engines of similar size, but employing different combustion chamber configurations. Silicon carbide was of interest as a DPF material because of its improved thermal properties (34) compared to Cordierite. It was believed that SiC would offer a performance comparable with Cordierite but would be less likely to suffer from interaction with sodium salts owing to lower regeneration temperatures in the monolith. Results of the tests carried out using sodium based additives with both DPF materials are discussed below.

## TEST ENGINES

Two 1.9 litre passenger car diesel engines were used for the test work. Details of both engine types are given in Table 1 below.

Table 1. Details of engines used for test work

| Engine code | A | B |
|---|---|---|
| Engine configuration | Turbocharged direct injection | Naturally aspirated indirect injection |
| Engine type | IZ | XUD 9A |
| Bore (mm) | 79.5 | 83.0 |
| Stroke (mm) | 95.5 | 88.0 |
| Displacement (cm$^3$) | 1896 | 1905 |
| Compression ratio | 19.5 : 1 | 23.0 : 1 |
| Maximum power (kW) | 66 | 52 |
| Maximum power speed (rpm) | 4000 | 4600 |
| Maximum torque (Nm) | 202 | 120 |
| Maximum torque speed (rpm) | 1900 | 2000 |

Test work on engine A was carried out at an independent laboratory with access to particle size measuring equipment, ie. a scanning mobility particle sizer (SMPS). The installation for bed engine A is shown in Figure 1.

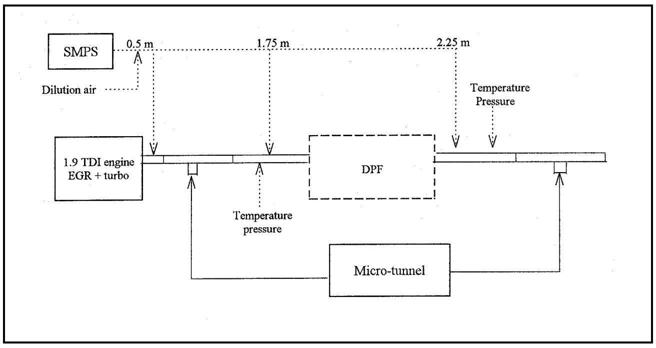

Figure 1. Experimental set up with engine A

The DPF was installed about 1.75 m from the engine as shown. Measurements of particulate mass were made using probes located both upstream and downstream of the DPF, feeding into a micro dilution tunnel. Analysis of particulates yielded data on inorganic fraction (IOF) and soluble organic fraction (SOF).

Measurements of the size distribution and number of particles were made using the SMPS. Samples were taken both upstream and downstream of the DPF as shown in Figure 1. It was found to be necessary to dilute SMPS samples to prevent condensation or agglomeration of particles in the sample lines. A dilution ratio of about 20 was used. The characteristics of the SMPS particle size measuring device are described in a CONCAWE document (35).

Bosch smoke measurements were also made as part of the experimental work. Related work investigating DPF performance, and measuring particle size distribution was reported in 1997 (36). This paper covered base fuels only, and did not report findings from tests on fuel containing a sodium based additive.

Engines A and B were operated on different blends of diesel fuel, both meeting the specification for European automotive diesel fuel, EN 590. The EN 590 specification, which is shown in Appendix 1, limits fuel sulphur content to 500 ppm weight.

A sodium based additive was used for the test work with both engines, although treat rates were different. For tests with engine A, the treat rate equated to 5 ppm sodium, while the additive used for test work with engine B was a sodium based product also containing traces of strontium. For work with engine B, total metal treat rate was 20 ppm.

## TEST WORK WITH ENGINE A

Initial tests assessed engine out effects of the additive on smoke and particulate mass. Tests were carried out at three engine speeds and three different load conditions, giving a matrix of nine speed/load points, as follows:

| Speed, rev/min | Torque, Nm |
|---|---|
| 2000 | 30, 90, 150 |
| 3000 | 30, 90, 150 |
| 4000 | 30, 90, 150 |

Results of engine out tests with and without additive are shown for particulates and smoke emissions, in Figures 3 and 4 respectively. The data show that while there is no significant difference in mass of particulates and smoke emissions from the use of the additive, the general trends indicate reduced levels of both pollutants with additive treated fuel.

Figures 3 and 4: Particulates and smoke emissions with and without additive: engine A

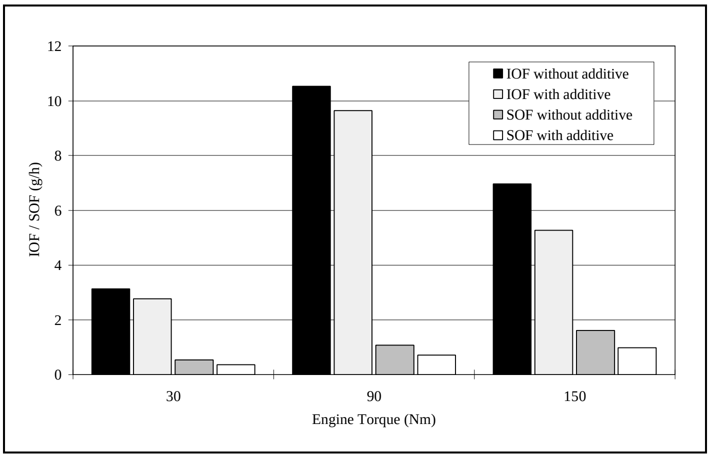

Figure 3a. Engine speed 2000 rev/min - particulates (IOF, SOF)

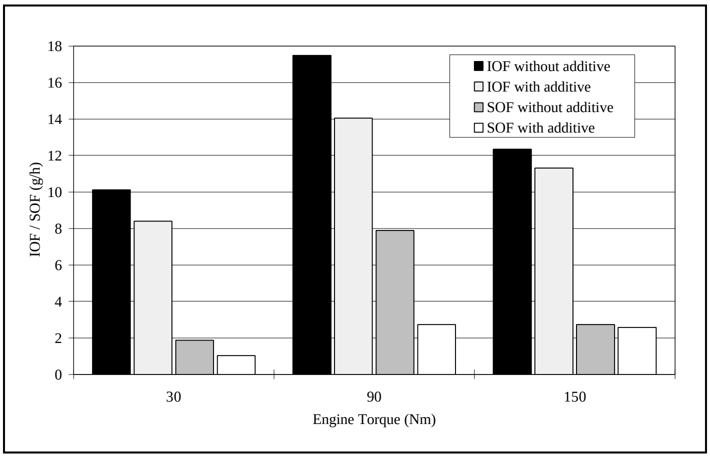

Figure 3b. Engine speed 3000 rev/min - particulates (IOF, SOF)

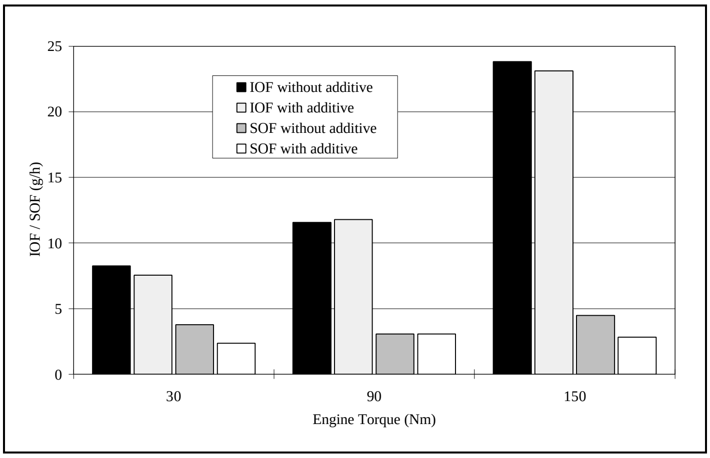

Figure 3c. Engine speed 4000 rev/min - particulates (IOF, SOF)

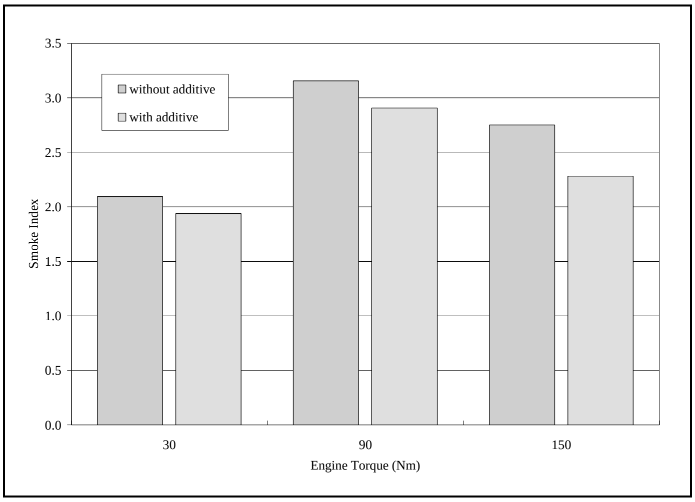

Figure 4a. Engine speed 2000 rev/min - Bosch smoke index

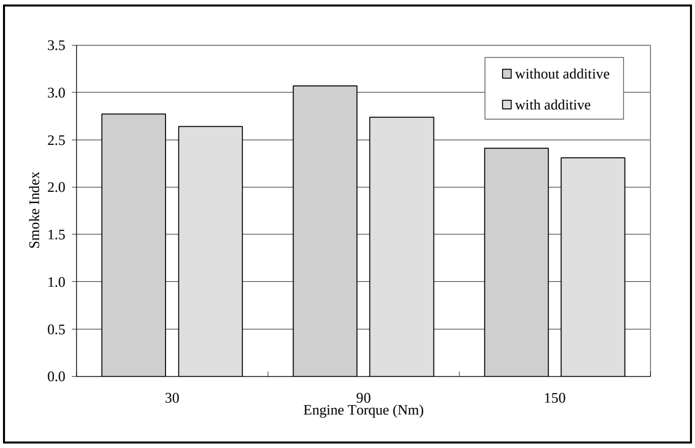

Figure 4b. Engine speed 3000 rev/min - Bosch smoke index

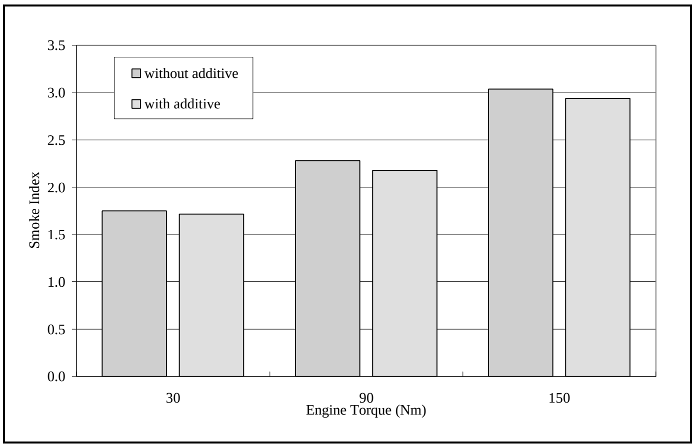

Figure 4c. Engine speed 4000 rev/min - Bosch smoke index

Further engine out tests were carried out to measure particle size distribution, with and without additives. For these tests a matrix of four speed/load points was used, as follows:

| Speed, rev/min | Torque, Nm |
|---|---|
| 2000 | 30, 90 |
| 3000 | 30, 90 |

Results of these tests are shown in Figures 5 and 6, for engine speeds 2000 rev/min and 3000 rev/min respectively.

Figures 5a and 5b. Effect of additive on particle size at 2000 rev/min

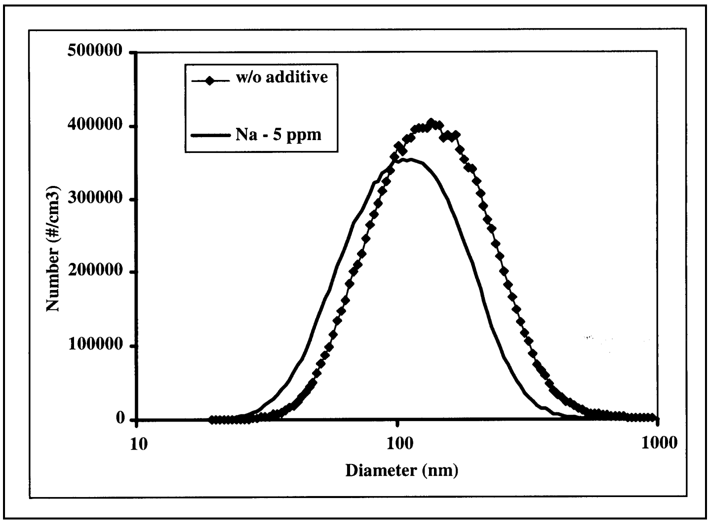

Figure 5a. Particulate size distributions - 2000/30

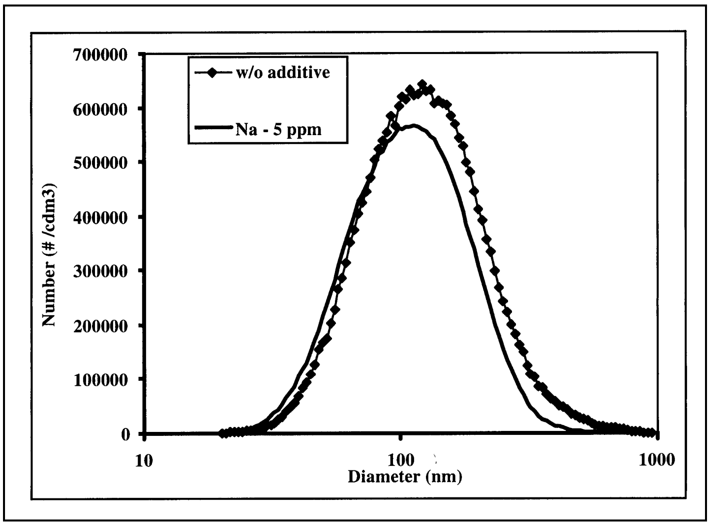

Figure 5b. Particulate size distributions - 2000/90

Figures 6a and 6b. Effect of additive on particle size at 3000 rev/min

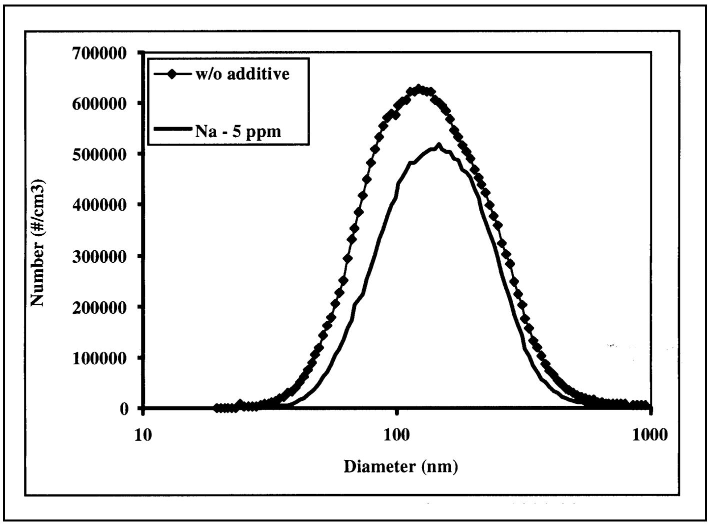

Figure 6a. Particulate size distributions - 3000/30

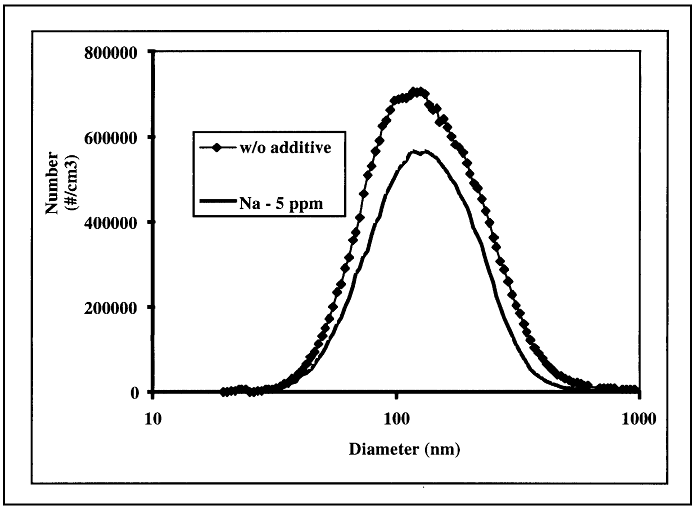

Figure 6b. Particulate size distributions - 3000/90

As for measurements of smoke and particulate mass, there is no significant difference in the effect of the additive on particle size, although general trends suggest a reduction in the number of particles when the additive is used. From the engine out tests carried out with and without the additive, there is significant confidence of no harmful effect in the test parameters examined, from the use of the metallic additive.

Work was also carried out using the sodium based additive in combination with a DPF. Measurements of particulate mass made both upstream and downstream of the DPF allow filtration efficiencies to be calculated. Similar measurements of particle size distribution were made both upstream and downstream of the filter. Both types of measurements show major benefits from the use of DPF technology in reducing particulate emissions.

Filtration efficiencies for different DPF back pressures, measured when operating on the sodium based additive, are shown for two different load conditions, 30 and 90 Nm, at an engine speed of 2000 rev/min, in Figures 7a and 7b respectively.

Figures 7a and 7b. Filtration efficiency with additive treated fuel

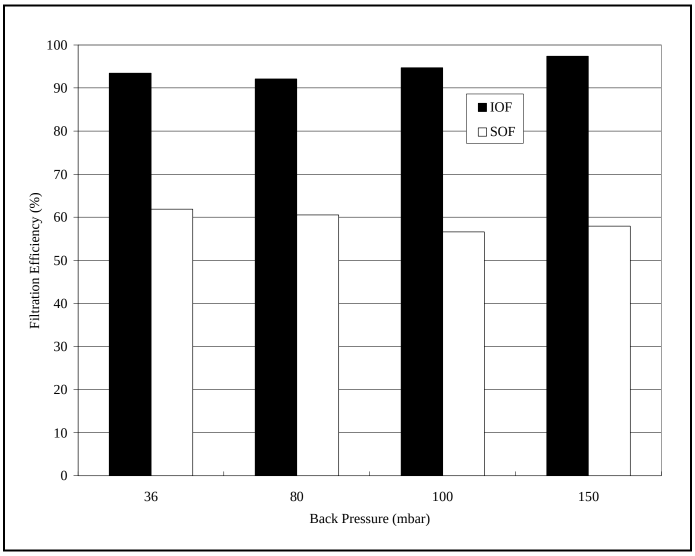

Figure 7a. Filtration efficiencies as a function of DPF back pressure, 2000 rev/min, 30 Nm

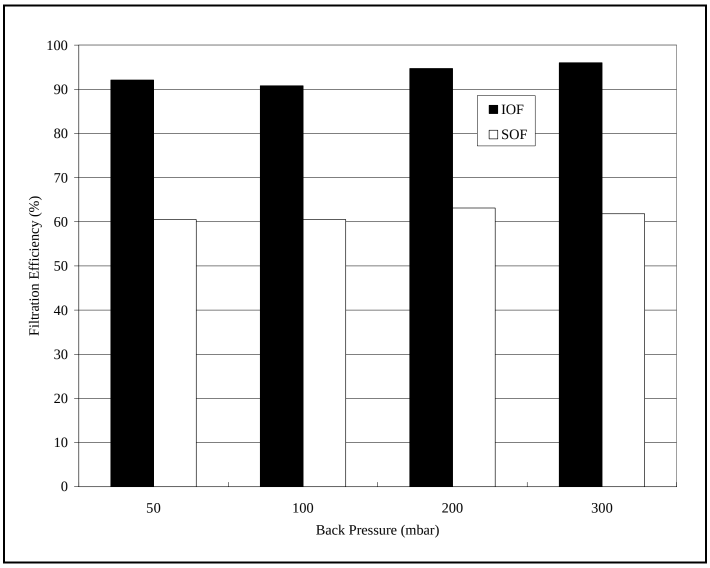

Figure 7b. Filtration efficiencies as a function of DPF back pressure, 2000 rev/min 90 Nm

Comparison of the filtration efficiency measured using additive treated fuel, with data reported earlier (36) for untreated fuel, shows no loss of filtration efficiency when additive treated fuel is used. Although differences are not significant, there is a trend towards higher filtration efficiencies when operating on fuel containing additive. In both cases, very high filtration efficiencies were demonstrated with the ceramic DPF tested, with a slight increase in efficiency as back pressure increased.

As is well known, the characteristics of a DPF alter continuously as material accumulates within the body of the filter. Back pressure increases, which can affect the transmission or leakage of particulate matter. Measurements made at different filter back pressure levels, corresponding to increasing accumulation of material within the DPF, show the effect on particle size distribution, both upstream and downstream of the filter.

Figures 8a and 8b show the particle size distributions measured upstream of the DPF at different DPF back pressures, for two engine operating conditions, running on additive treated fuel.

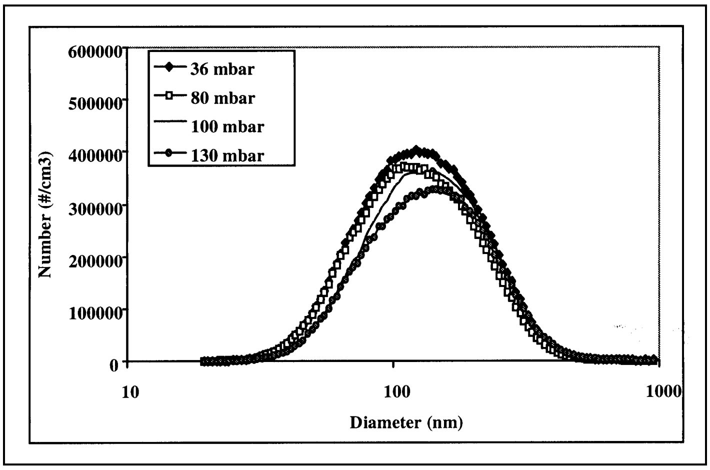

Figure 8a. Particle size distribution upstream of DPF as a function of DPF back pressure, 2000 rev/min, 30 Nm

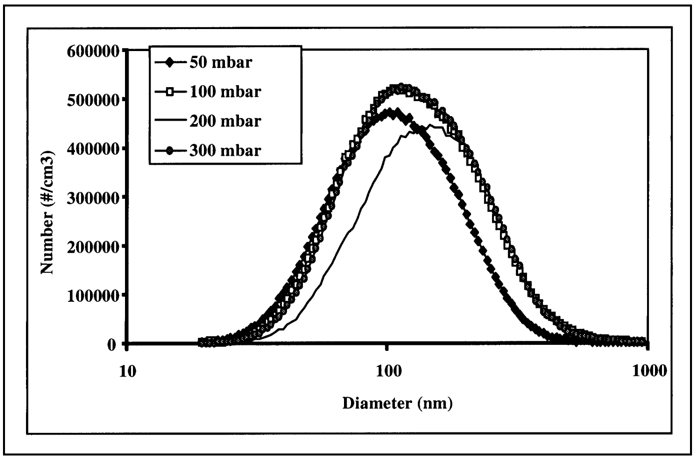

Figure 8b. Particle size distribution upstream of DPF as a function of DPF back pressure , 2000 rev/min, 90 Nm

Figures 9a and 9b show corresponding size distribution measurements made downstream of the filter when operating on additive treated fuel.

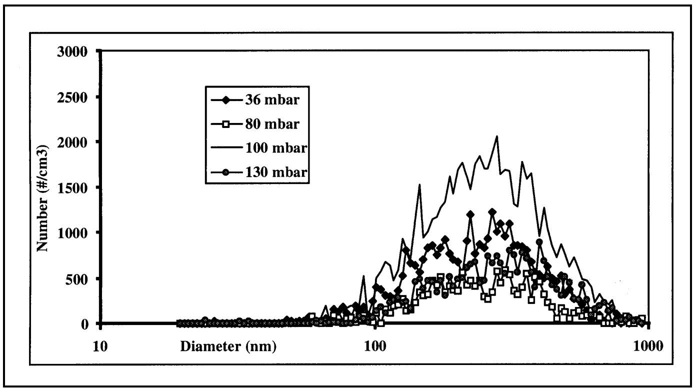

Figure 9a. Particle size distribution downstream of the DPF as a function of DPF back pressure, 2000 rev/min, 30 Nm

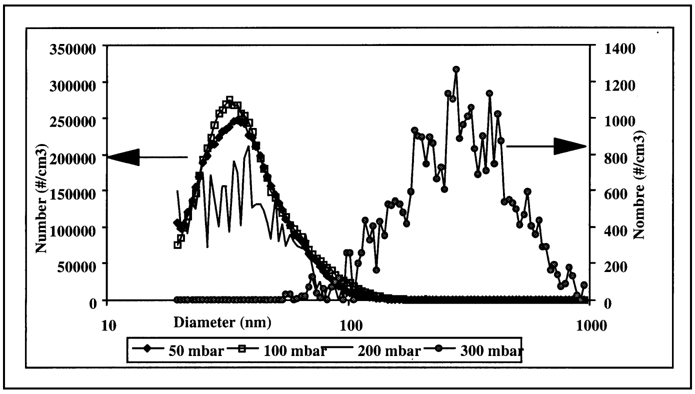

Figure 9b. Particle size distribution downstream of the DPF as a function of DPF back pressure, 2000 rev/min, 90 Nm

At low engine load, the number of particles emitted from the filter is reduced to a negligible level at all DPF loading conditions, when compared to upstream measurements. At the higher engine load condition, the number of particles emitted increases, both upstream and downstream of the filter.

The additional peak of fine particles emitted from the DPF at low filter loading has been interpreted as a mist of higher molecular weight hydrocarbons which would normally be adsorbed on to the surface of dry particulate matter (36). These are not retained in the filter under certain operating conditions. Data presented for untreated base fuel operation using the same DPF system show very similar results (36) leading to the conclusion that there is no adverse effect from additive use.

In summary, this comprehensive test programme, base fuel data from which has been published earlier (36), showed that the use of the sodium based additive had no adverse effect on:

- the operation of the engine upstream of any exhaust after treatment device
- the effectiveness of DPF efficiency in trapping particulate matter
- the size distribution of particulate matter emitted from the engine or from the DPF.

## TEST WORK WITH ENGINE B

Work with engine B concentrated on evaluating the performance of the sodium based additive in a ceramic DPF. In this case, after initial work with Cordierite, the material employed in the filter was silicon carbide. The engine was mounted on a pallet arrangement equipped with appropriate heat exchangers, electrical connections and connectors for instrumentation signals. This pallet arrangement was connected to the engine test bench. The engine dynamometer was a Froude AG150 eddy current machine controlled by the CP Engineering Cadet system. The engine temperatures were controlled automatically by suitable 3-term controllers integrated into the secondary coolant system supplies. The test bench was controlled and data logged using a CP Engineering Cadet system.

The engine exhaust system was modified to allow ready interchange of a centre section which could incorporate a selection of DPFs. For the work reported here a silicon carbide DPF (type L3-Ø144xL154-F820-1-SF) was installed. The DPF was fitted with 12 thermocouples positioned as in Figure 10. Details of the material properties of SiC can be found in reference 34.

## DEVELOPMENT OF TEST METHOD

Initial tests were performed on engine B with a Cordierite DPF to try to replicate previous experience from tests with a Peugeot 309 car (fitted with an XUD-9 engine) running on a chassis dynamometer.

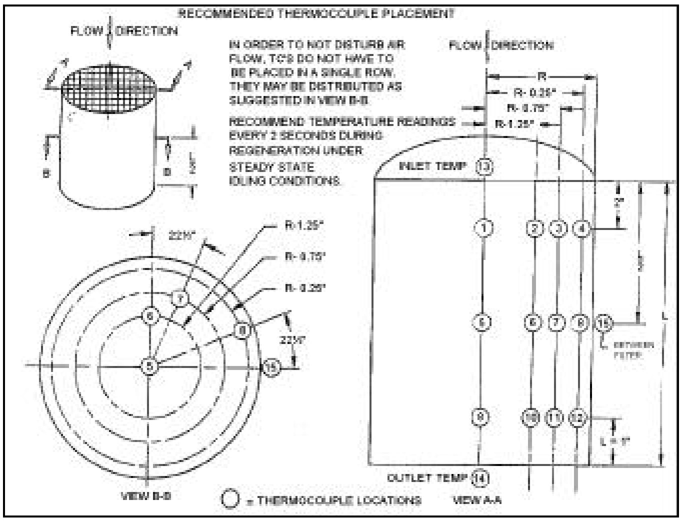

Figure 10. Thermocouple placement

An engine speed of 3000 rev/min was selected, and the load adjusted to give a DPF inlet temperature of 190 to 195°C. However, this equated to a very low load, and consequently the temperature requirements were relaxed and an engine load of 20 Nm was selected. This gave a DPF inlet temperature of greater than 200°C. Although the additive package had performed well on the car, giving frequent stochastic regenerations, its performance on the test bench was less satisfactory, despite the higher temperatures, with forced regenerations required. This is shown in Figure 11.

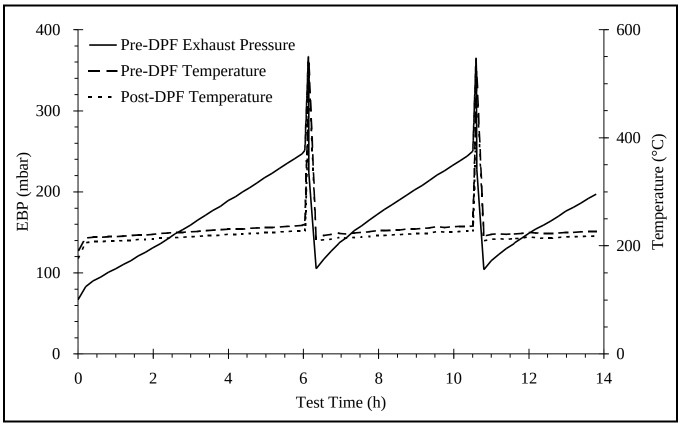

Figure 11. Forced regenerations at 3000 rev/min, 20 Nm.
Maximum Post-DPF temperature = 517°C

The combination of relatively high speed and low load was felt to be producing a “dry” soot which was not very conducive to regeneration. “Wetter” soot was considered to result from lower speed, higher load conditions.

An alternative operating condition was therefore, investigated, with an engine speed of 1840 rev/min, which equated to the car travelling at 70 km/h in fifth gear. To obtain the desired DPF inlet temperature at this speed required an engine torque of 30 Nm. Although the performance was not as good as anticipated, stochastic regenerations were observed, as shown in Figure 12.

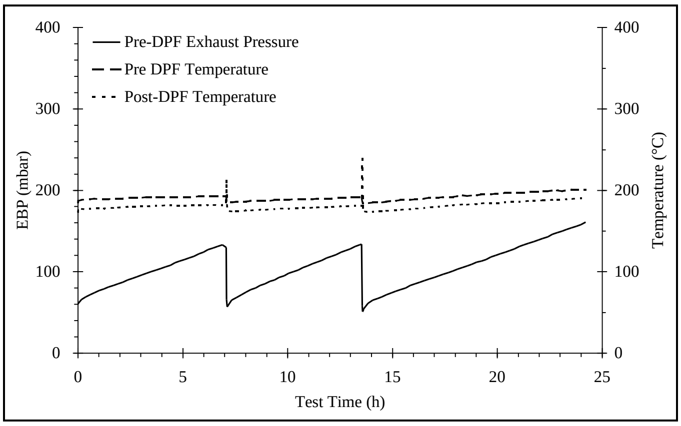

Figure 12. Stochastic regenerations at 1840 rev/min, 30 Nm. Maximum Post-DPF temperature = 238°C

It had previously been assumed that stochastic regenerations would occur within the DPF, if the right conditions of temperature and oxygen were satisfied. The initial testing had indicated that this was not necessarily the case. It was thus proposed to test the regeneration characteristics of the DPF system over a wider range of steady state operating conditions.

For this proposed work, the DPF material was changed from Cordierite to silicon carbide. The necessary installation was made up, and the filter unit instrumented with thermocouples, using the arrangement shown in Figure 10. The completed assembly was fitted into the bed engine exhaust system in place of the Cordierite DPF. This was easily achieved, as this section of the exhaust system had been made readily demountable and interchangeable as described earlier.

A matrix consisting of nine engine speeds and nine engine torques was drawn up. As it was originally anticipated that 24 hours of running would be required to assess the regeneration performance at each condition, a matrix of 81 test sites would clearly not be practical. As the initial test work had shown that there was a condition at which the DPF would regenerate stochastically, and conditions at which it would not, it was assumed that within the engine operating range (the test matrix) there would be a region in which the DPF would operate, and a region where it would not. The aim therefore was to try and define the boundary of this region rather than to test over the entire matrix. The initial tests would act as a starting point from which the final test matrix would evolve. Table 2 shows the points within the matrix at which testing was eventually conducted.

Table 2. Test matrix

| | | Engine speed (rev/min) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1260 | 1550 | 1840 | 2130 | 2420 | 2710 | 3000 | 3580 | 4160 |
| Engine Torque (Nm) | 20 | ✓ | ✓ | | ✓ | | | | | |
| | 25 | ✓ | ✓ | ✓ | | | | | | |
| | 30 | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | |
| | 35 | ✓ | ✓ | | ✓ | | | | | |
| | 45 | ✓ | | ✓ | | ✓ | | ✓ | | |
| | 60 | ✓ | | ✓ | | ✓ | | ✓ | | |
| | 75 | | | ✓ | | ✓ | | | | ✓ |
| | 100 | | | ✓ | | ✓ | | ✓ | ✓ | |
| | full rack | | | ✓ | | ✓ | | ✓ | ✓ | |

The test cycle was devised to ensure survival of the DPF through the use of events and stage timing. The engine was started and then controlled to the constant speed/load conditions required for the individual test, by the CP Cadet control system. During the constant speed/load stages, data logging of critical engine parameters and DPF temperatures was carried out once every minute, averaged over 10 seconds, using the 12 internal thermocouples.

The test continued at a selected constant speed/load condition for the duration of the test. At the end of test the control system carried out a ‘forced regeneration’ to clean the DPF for the next condition. After five minutes, or when a sufficiently low exhaust back pressure (EBP) was reached, which ever was sooner, the control system idled the engine for five minutes before stopping. If at any time during the constant speed/load stage the EBP reached a pre-defined ‘critical’ limit, the control system moved to a ‘forced regeneration’ stage, where the engine speed and load were increased to 3500 rev/min and 110 Nm over 7 mins 30 seconds. During this time, data logging rates were increased to every 10 seconds for engine parameters, but no data logging was carried out for fuel consumption. If the EBP dropped below a pre-determined limit, the control system returned to the constant speed/load stage, but after 10 minutes if the EBP had not reduced sufficiently the test was stopped. If at any time the DPF outlet temperature exceeded 750°C, the control system moved to a ‘safety stage’, where the engine was controlled to 3000 rev/min and 5% fuel rack. If the DPF outlet temperature reduced to below 500°C then the control system reverted back to the constant speed/load condition. However, if the temperature had not reduced sufficiently after five minutes then the test was terminated.

## RESULTS AND DISCUSSION

Figure 13 summarises the results: a solid marker indicates that the DPF would reliably self regenerate at that operating condition. A cross marker indicates that the EBP reached the arbitrary limit, and a regeneration was forced.

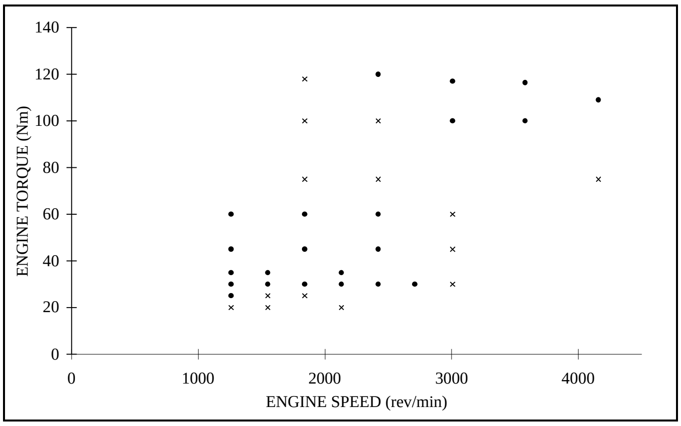

Figure 13. Summary of areas of reliable self regeneration

It is clear from Figure 13 that there is a region towards the bottom left of the chart where the system (DPF and additive) would work well, indicated by the solid markers. There is also a region in the top right of the chart where the system worked well. However, there is a large region in between where the system did not appear to work, indicated by the crosses. Figure 14 shows an operating speed/load condition where stochastic regenerations occurred.

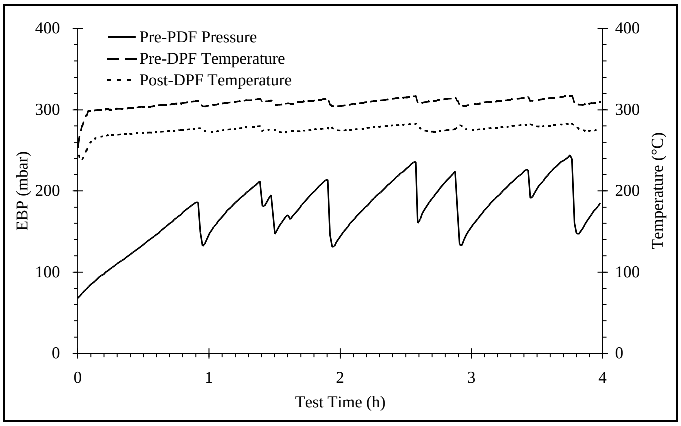

Figure 14. Stochastic regenerations at 1840 rev/min, 60 Nm. Maximum Post-DPF temperature = 283°C

If the arbitrary EBP limit had been reduced to 200 mbar, then a forced regeneration would have been initiated. From this it is clear that if the arbitrary EBP limits had been set lower, the region where a forced regeneration was required would increase. It could therefore be argued that if the arbitrary EBP limits had been set higher, the region of stochastic regeneration would increase. This may be so, however, further work would be required to investigate to what extent EBP can be allowed to rise before engine operation is severely compromised, or a catastrophic exothermic reaction becomes a probability. If the arbitrary EBP limits are maintained, subsequent testing at the boundaries of the solid marker region can be used as a measure of relative system performance, for example to evaluate different additives and DPF materials.

Although the regeneration characteristics of the DPF are not yet fully understood, some theories may be postulated. From Figure 15 it can be seen that the EBP was relatively constant, ie. the DPF appears to be in equilibrium.

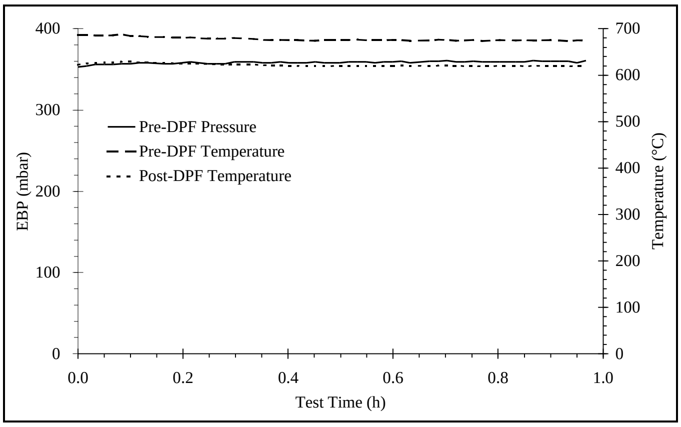

Figure 15. EBP equilibrium at 3580 rev/min, full rack. Maximum Post-DPF temperature = 629°C

This was not unexpected, as the temperatures within the DPF were in excess of 600°C, and at these temperatures soot should oxidise without the aid of any catalytic agent. It is therefore reasonable to assume that soot being deposited on the DPF was being oxidised at the same rate as it was being deposited. Therefore the original assumption, that if oxygen is present and at a sufficient temperature, the DPF will automatically regenerate, holds true. In this case the regeneration threshold temperature is the autoignition temperature of carbon. If we consider the lower left corner of the operating range shown in Figure 13, temperatures are much lower but oxygen levels are higher. Figure 16 shows a case where the DPF inlet temperature never exceeded 175°C, yet stochastic regenerations occurred.

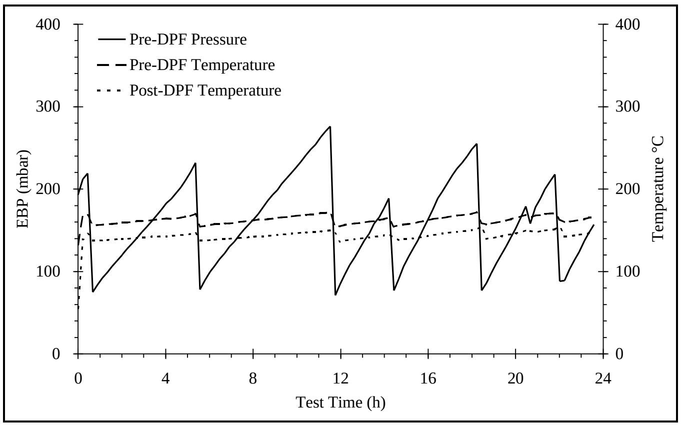

Figure 16. Stochastic regenerations at 1260 rev/min, 25 Nm. Maximum Post-DPF temperature = 159°C

As carbon will not oxidise at this temperature without the aid of a catalyst, the additive must be catalysing the regeneration process. However, Figure 17 shows a case where the temperature was above 200°C, and yet the catalytic effect of the additive seems to be lost.

Knowledge of the performance of diesel engines suggests that at the low speed/low duty conditions represented by Figure 16, the particulate matter deposited in the DPF will contain a significant amount of adsorbed unburned, or partly burned fuel (ie. the ‘wet’ soot referred to earlier). At the higher speed represented by Figure 17, this soluble fraction of the particulate is likely to be smaller (ie. ‘dry’ soot).

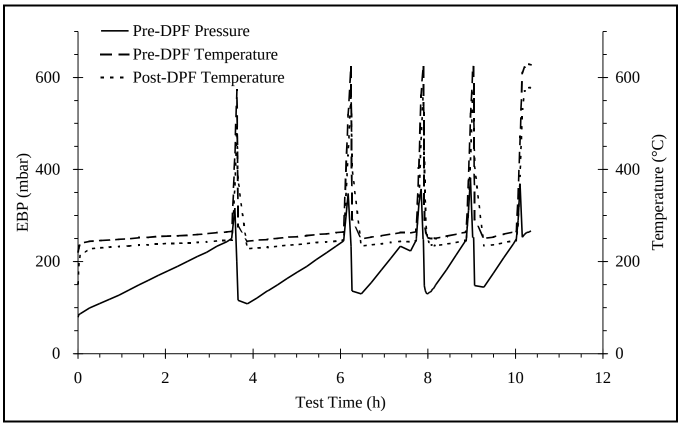

Figure 17. Forced regenerations at 3000 rev/min, 30 Nm Maximum Post-DPF temperature = 578°C

It may thus be postulated that the regeneration threshold temperature is defined by the nature of the particulate matter deposited within the DPF, and not just by the activity of the catalyst resulting from the fuel additive. This may explain why regeneration will take place at tempertures below 175°C, however, further work is required to assess this phenomenon.

During stochastic regenerations, temperature excursions caused by regeneration, of the order of 25-90°C were recorded, as shown in Figure 18. These temperature excursions compared favourably with similar events measured in a Cordierite DPF, where markedly larger temperature excursions, perhaps of 200°C were recorded under similar operating conditions.

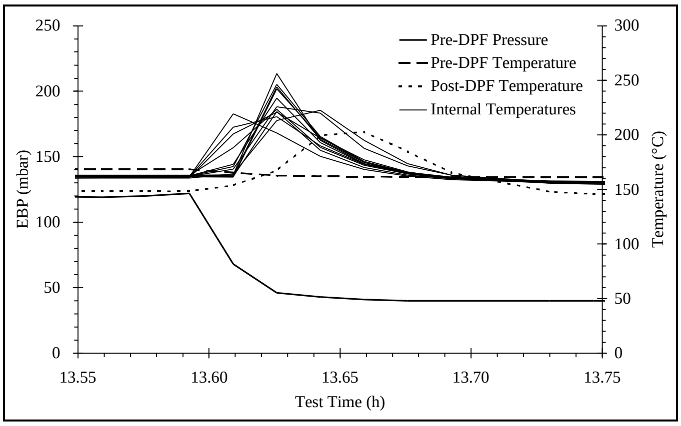

Figure 18. Stochastic regeneration at 1260 rev/min, 30 Nm

Where forced regenerations became necessary, as a result of reaching the predetermined EBP limit, high gas temperature and pressure conditions occurred through increased engine speed and load. Under these conditions, as shown in Figure 19, peak temperatures in the core of the DPF reached 600-630°C.

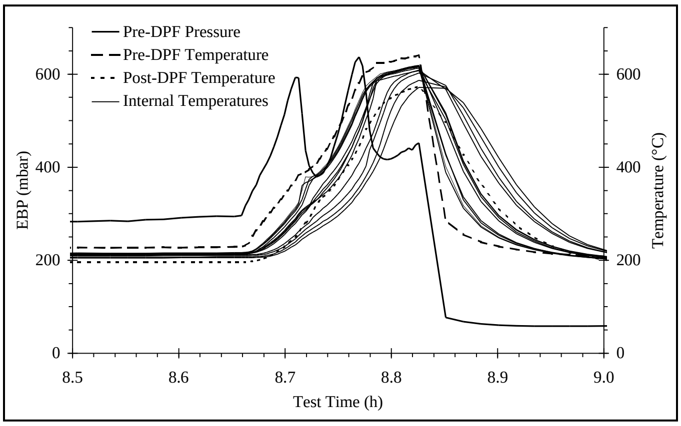

Figure 19. Forced regeneration at 1260 rev/min, 45 Nm

The DPF maintained a constant running temperature of 670-680°C for approximately one hour with no detrimental affects as shown in Figure 15.

## CONCLUSIONS AND RECOMMENDATIONS

A comprehensive test programme on a ceramic diesel particulate filter system carried out using engine A, and employing both particulate mass and size distribution measuring equipment, showed that the use of a sodium based additive in the diesel fuel had no adverse effect on:

- the operation of the engine upstream of any exhaust after treatment device
- the effectiveness of the filter efficiency in trapping particulate matter
- the size distribution of particulate matter emitted from the engine or from the particulate filter.

From the work described with engine B, a silicon carbide DPF system seems to be a viable alternative to Cordierite, with a sodium based additive. SiC has favourable material properties, the most important being its high thermal conductivity leading to smaller temperature excursions during regeneration than those seen with Cordierite. This indicates that it is unlikely to suffer interaction between the additive and the ceramic monolith. In addition to this, work carried out by the manufacturers of the SiC DPF systems show that it is able to withstand higher temperatures under severe regenerations, with significantly lower risk of melting, than Cordierite.

Due to the favourable regeneration results seen with the sodium based additive, and the low temperatures achieved during these regenerations, the investigation of alternative additives using SiC DPF technology is proposed. The current belief is that the sodium additive forms sodium sulphates, carbonates and peroxides during combustion. Above 850°C, these become molten and interact with the ceramic DPF material. An additive whose products of combustion either become molten at much higher temperatures, or do not react with ceramic DPF materials, would be of interest as a potential alternative to sodium and strontium combinations. However, candidate additives would also need to demonstrate equivalent or superior regeneration characteristics to those already shown by sodium and strontium additive combinations.

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# APPENDIX 1

General specification for European diesel fuel meeting the requirements of EN 590*

Table 1. Generally applicable requirements and test methods

| Property | Units | Limits | | Test methods |
|---|---|---|---|---|
| | | minimum | maximum | |
| Flash point | °C | above 55 | - | EN 22719 |
| Carbon residue (on 10% distillation residue) | % (m/m) | - | 0.39 | EN ISO 10370 |
| Ash content | % m/m | - | 0.01 | EN ISO 6245 |
| Water content | mg/kg | - | 200 | prEN ISO 12937:1996 |
| Total contamination | mg/kg | - | 24 | prEN 12662:1996 |
| Copper strip corrosion (3h at 50°C) | rating | class 1 | | EN ISO 2160 |
| Oxidation stability | g/m$^3$ | - | 25 | EN ISO 12205 |
| Sulfur content | % (m/m) | - | 0.050 | EN 24260<br>EN ISO 8754<br>prEN ISO 14596:1996 |
| Lubricity, corrected wear scar diameter at 60°C | µm | - | 460 | CEC F-06-A-96[1] |
| [1] It is intended that this method will be replaced by ISO 12156-1 on publication | | | | |

Table 2. Climate-related requirements and test methods

| Property | Units | Limits | | Test methods |
|---|---|---|---|---|
| | | minimum | maximum | |
| CFPP | °C | | | EN 116 |
| CFPP grade A | | - | +5 | |
| CFPP grade B | | - | 0 | |
| CFPP grade C | | - | -5 | |
| CFPP grade D | | - | -10 | |
| CFPP grade E | | - | -15 | |
| CFPP grade F | | - | -20 | |
| Density at 15°C | kg/m$^3$ | 820 | 860 | EN ISO 3675<br>EN ISO 12185 |
| Viscosity at 40°C | mm$^2$/s | 2.00 | 4.50 | EN ISO 3104 |
| Cetane number | | 49.0 | - | prEN ISO 5165:1997 |
| Cetane index | | 46.0 | - | EN ISO 4264 |
| Distillation | | - | | ISO 3405 |
| % (v/v) recovered at 250°C | % (v/v) | | < 65 | |
| % (v/v) recovered at 350°C | % (v/v) | 85 | - | |
| % (v/v) recovered at 370°C | % (v/v) | 95 | - | |

* currently under review

THE ASSOCIATED OCTEL COMPANY LIMITED
FUEL TECHNOLOGY CENTRE
BLETCHLEY

# Particulates Reduction in Diesel Engines Through the Combination of a Particulate Filter and Fuel Additive

**BY**

**M W Vincent**
**P Richards**
**S L Cook**

(For presentation to SAE F & L Congress, Ocobter 1998)

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