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Linking the Physical Manifestation and Performance Effects of Injector Nozzle Deposits in Modern Diesel Engines

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ABSTRACT

The formation of deposits within injector nozzle holes of common-rail injection fuel systems fitted to modern diesel cars can reduce and disrupt the flow of fuel into the combustion chamber. This disruption in fuel flow results in reduced or less efficient combustion and lower power output. Hence there is sustained interest across the automotive industry in studying these deposits, with the ultimate aim of controlling them.

In this study, we describe the use of Scanning Electron Microscopy (SEM) imaging to characterise fuel injector hole deposits at intervals throughout an adaptation of the CEC Direct Injection Common Rail Diesel Engine Nozzle Coking Test, CEC F-98-08 (DW10B test)[1].

In addition, a similar adaptation of a previously published Shell vehicle test method [2] was employed to analyse fuel injector hole deposits from a fleet of Euro 5 vehicles. During both studies, deposits were compared after fouling and after subsequent cleaning using a novel fuel borne detergent.

In all cases, the use of fuel borne detergents quickly recovered >75% of power lost during the fouling stage of the tests. SEM images showed that the removal of deposits within the injector nozzle holes was key to the recovery of power and that deposits on the injector nozzle exterior could be misleading in predicting the performance of fuel injectors.

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INTRODUCTION

The formation of deposits within the nozzle holes of modern direct-injection diesel engines can reduce the quantity and disrupt the spray pattern of fuel injected into the combustion chamber. The reduced or less efficient combustion that results gives lower power and increased fuel consumption and emissions [3, 4, 5]; therefore studying the formation, removal and control of these deposits is of great interest.

Prior studies in this field [6, 7, 8, 9, 10] have shown that the speed and load of a given drive cycle (i.e. an individual's driving style), fuel composition (presence of trace elements, such as zinc), and the inherent sensitivity of the engine design can affect the formation of such deposits.

Modern diesel engines are designed to deliver on a set of competing parameters: high power density, low fuel consumption, reduced Noise, Vibration and Harshness (NVH) and whilst being required to conform to stringent emissions standards. The evolution of the modern diesel engine to meet these design parameters has seen the adoption of engine downsizing and increasingly complex exhaust after treatment as well as an over-riding need for precision control of combustion.

More recent fuel injection equipment (FIE) innovations to address precision control of combustion include increasingly high pressure common rail systems with multiple injection events to deliver precise control and metering of injected fuel quantity. High hydraulic efficiency fuel injector nozzles featuring an increased number of smaller diameter tapered and honed nozzle holes have also been adopted.

Potential side-effect of these trends, which could increase susceptibility to injector nozzle fouling are high pressure common rail systems thermally stressing re-circulated fuel, and reduced cavitation-cleaning of deposits in high hydraulic efficiency injector nozzles.

Further deployment of FIE using increasing common rail pressures and high hydraulic efficiency injector nozzles to comply with emerging emissions regulations (Euro 6 & Tier 2 bin 5) and the need to comply with these emissions standards throughout the useful lifespan of the vehicle [11][12] could mean that fouling of fuel injector holes continues to be a relevant issue in future vehicles.

The objective of the program outlined in this paper was to gain insight into the physical manifestation of injector nozzle hole deposits and their response to fuels and additives and link this to their effects on performance. Techniques employed were purposely non-destructive so that analysed injectors could be refitted to the engines enabling series measurements to be made. Physical manifestation of the deposits was evaluated using Scanning Electron Microscopy (SEM) imaging and in some samples, Energy-Dispersive X-ray spectroscopy (EDX) techniques. Initial measurements were made in an adaptation of the industry standard DW10B engine fouling test [1] and then compared to deposits formed *in vehicle* during chassis dynamometer testing in a range of modern (Euro 5) vehicles. Performance effects of deposits were measured by evaluating steady state engine power output.

In this study, only deposits on the injector nozzle body and inside the injector nozzle hole are considered; deposits formed on surfaces internal to the injector (Internal Diesel Injector Deposits - IDID's) are not implicated in this mode of testing and were therefore outside the scope of this study.

STUDYING FUEL INJECTOR HOLE DEPOSITS IN A COMMON RAIL DIRECT INJECTION TEST ENGINE

The CEC Direct Injection Common Rail Diesel Engine Nozzle Coking Test, CEC F-98-08 (DW10B test) [1] is the industry standard test for evaluating fuel and additive effects on injector nozzle coking (fouling) in European diesel passenger cars with Direct Injection (DI) engines. The test uses a Euro 4 PSA DW10B 2.0L, Common-Rail, 4 cylinder, turbo-charged engine and relies on the following key factors to increase its baseline sensitivity to the formation of injector nozzle deposits:

- It is fitted with non-standard, prototype injectors designed to be sensitive to deposit formation. These feature tapered and honed nozzle holes that reduce cavitation cleaning [13], and are of a valve covered orifice design, which can allow hot exhaust gas to be drawn into the nozzle hole after an injection event.
- It requires zinc to be added to the reference fuel (at 1 mg/kg) to accelerate deposit formation rates to emulate substantial mileages that would not be practical in engine test scenarios.
- It features a cycle dominated by high load running to accelerate deposit formation.

A DW10B test engine running an adaptation of the CEC F-98-08 method was used to evaluate the physical manifestation of injector nozzle deposits in conjunction with their effect on engine power. The injectors were removed for SEM imaging periodically through the test.

Experimental

Test Engine

The test engine set up used was as per the CEC F-98-08 (DW10B) test [1]:

Table 1. Particulars of DW10B engine used in the CEC F-98-08 test

Engine code	DW10BTED4
Donor Vehicle	Peugeot 407 2.0 HDi 16v
Chassis number series	21010347
Displacement/layout	1998 cc / I4
Output	100kW at 4000 r/min
Peak torque	320Nm at 2000 r/min
EMS	Continental/Siemens
Injection system	Common rail, 1600 Bar peak pressure, piezo actuated injectors, 6 hole nozzles
Emissions	Normally certified to Euro 4; vehicle uses Exhaust Gas Recirculation (EGR) and Diesel Particulate Filter (DPF)

Test fluids

A 16 hour break-in run of a new injector set was carried out as per the CEC F-98-08 testing procedure; fuel was CEC DF-79-07 (Batch 6) without any additives or FAME.

For the dirty-up phase, an EN590 compliant, refinery sourced zero sulphur diesel (ZSD) was selected instead of the CEC Reference DF-79-07 fuel for testing to represent real world fuels. The B0 base fuel was blended with 7% of EN14214 certified Rapeseed Methyl Ester (RME) to represent the use of bio-fuels worldwide. As per CEC F-98-08, 1 mg/kg zinc (neodecanoate counter-ion) was added. Concentrations of zinc were confirmed by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES).

The clean-up fuel was identical to the dirty up fuel, but with the addition of a novel fuel-borne detergent.

In a variation from the established CEC method, an alternative lubricant, with an increased concentration of anti-wear additives was used to enhance engine durability.

Table 2. Particulars of the test fuels for DW10B engine tests

Fuel	Base Fuel	Target Zn Concentration (mg/kg)	Measured Zn Concentration (mg/kg)	Novel Detergent Package
Run-in	CEC DF-79-07 (Batch 6)	0	0	
Dirty-Up	B7 (ZSD + 7%v/v RME)	1.00	0.80	
Clean-Up		1.00	1.00-1.02	x

Test Cycle

The speed/load cycle employed throughout the engine test was as per CEC F-98-08. Please see the appendix for details.

Cold soaks were omitted from the test cycle, except where the engine was stopped to allow for injector removal and imaging by SEM.

Test Procedure

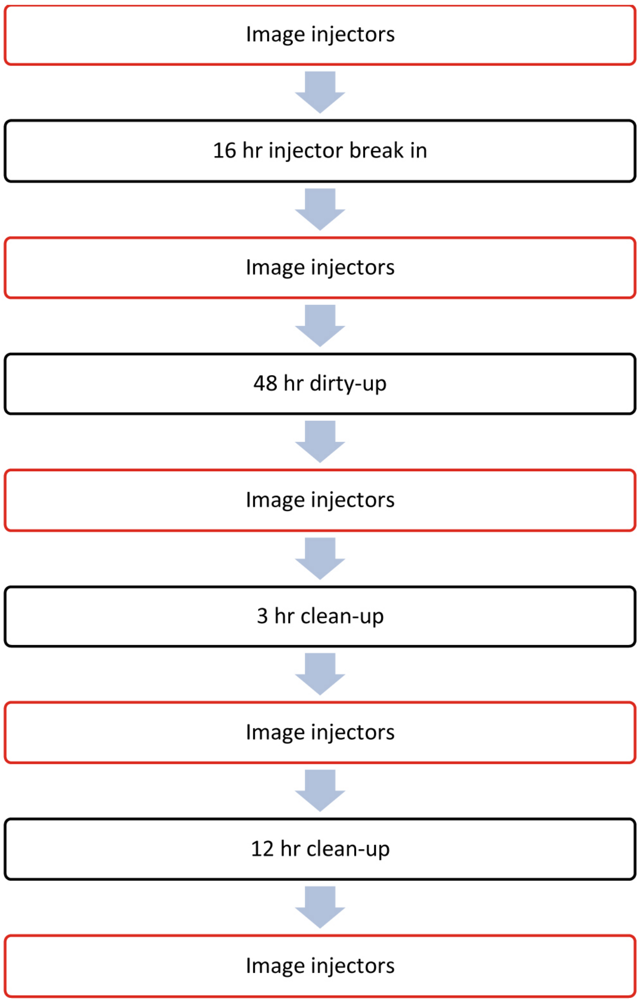

Figure 1. Test protocol for studying fuel injector hole deposits in a common rail direct injection test engine.

Analysis of Fuel Injector Hole Deposits

Fuel injectors were removed from the engine, while taking care not to damage any deposits on the injector tip, before preparation for SEM (via backscattered electron imaging), which was performed under variable pressure at 20 kV. EDX spectra data were also collected to gain information on the elemental content of the deposit layer; however the EDX data were corrupted and hence is not discussed. Further details on the SEM analysis can be found in the appendix.

Results of Study of Fuel Injector Hole Deposits in a Common Rail Direct Injection Test Engine

Maximum Power Measurements

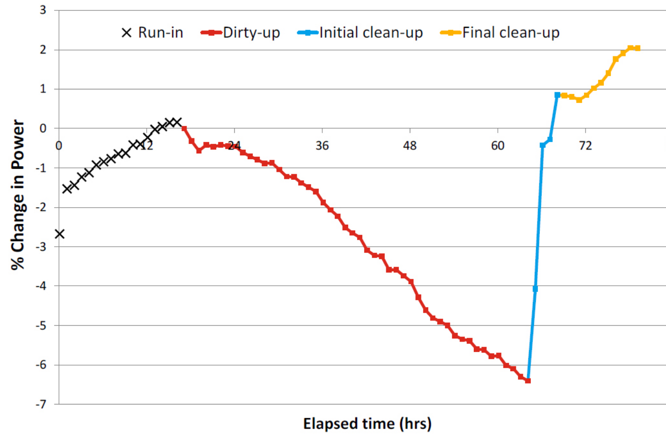

Figure 2. Percent change in power output during dirty-up and clean-up; note that the >100% power recovery is in line with the upward trend exhibited by the engine during the run-in.

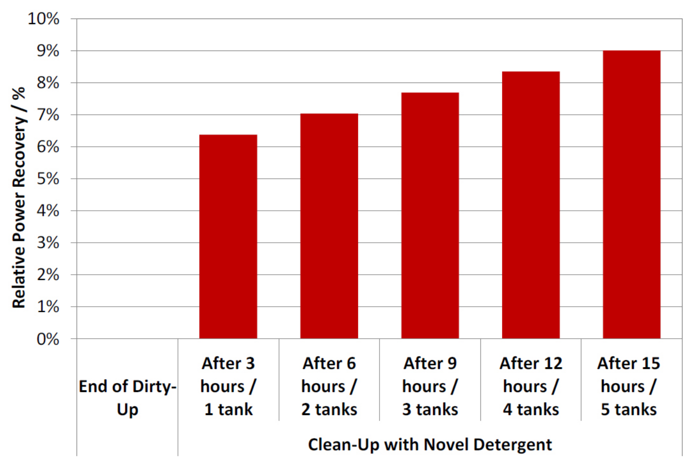

Figure 3. Relative power output of the test engine through the clean-up phase.

SEM Images of Injector Nozzle Holes Throughout Test

Back Scattered Electron Images

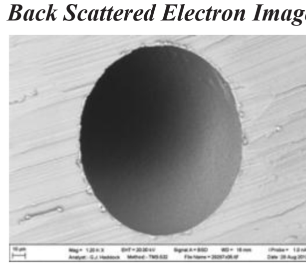

Figure 4. Clean Injector Hole (Prior to test commencement). Manufacturing marks on the outer surface and a smooth finish in the hole are evident

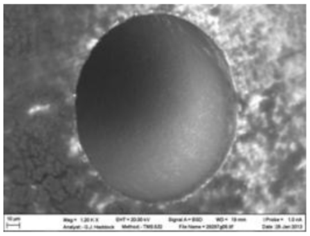

Figure 5. Bedded in Injector (16 hours bedding in, as per CEC F-98-08) A substantial deposit layer has formed on the outer surface but only light deposits are evident in the hole

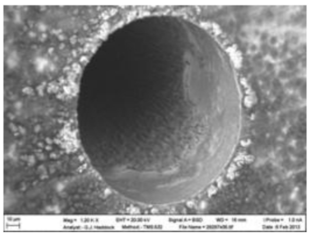

Figure 6. End of Dirty-Up. Deposits on the outer surface have increased and a thick deposit layer has formed in the hole

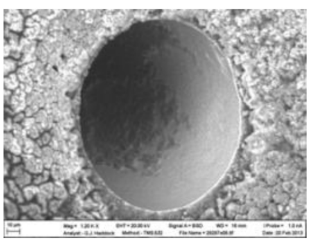

Figure 7. After 3 hours Clean-Up (66 litres - 1 tank). Deposits continue to accumulate on the outer surface and the deposits inside the hole are substantially reduced.

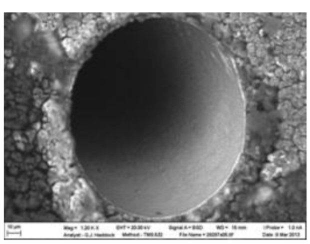

Figure 8. End of Clean-Up. Deposits continue to accumulate on the outer surface but have been completely removed from the nozzle hole.

Summary of bench engine study

Injector nozzle hole deposits have been studied in an adaptation of the industry standard CEC F-98-08 DW10B test with the aim of understanding the physical manifestation and performance effects of the deposits during formation and removal using a market realistic refinery sourced fuel containing FAME (B7).

The study of injector deposits through SEM imaging has visually linked the severity of deposits within the injector hole with the magnitude of power loss and recovery. Deposits outside of the nozzle hole increased with engine run time and were not linked to power loss or recovery as they do not affect delivery of fuel into the combustion chamber. N.B. The rough surface morphology of deposits outside the injector hole lead to an increase in charging, giving their bright appearance in the SEMs, and is not indicative of the depth of deposits.

The mechanism for the effect of visible nozzle hole deposits on engine power is proposed to be a reduction in hydraulic efficiency of the nozzle hole. This is partly caused by the deposit layer reducing nozzle hole cross sectional area and partly from the visibly irregular deposit topography which will increase frictional flow loss; effectively reducing the flow capacity of the nozzle. Because the injected fuel quantity is metered on a time (not volume) basis, reduced nozzle flow capacity will reduce the amount of fuel passing through the injector into the cylinder available for combustion. Irregular deposits could also disrupt the fuel spray formation and atomisation, leading to reduced combustion efficiency or thermodynamic efficiency, resulting in increased emissions and reduced fuel efficiency and power.

Running the engine on the same zinc dosed dirty up fuel containing a novel detergent additive was proven to remove the deposits which were detectable through SEM and through recovery of lost power. The deposits were removed gradually as a function of time and/or fuel used. After 3 hours / 1 tank full of fuel equivalent, most of the power lost had been regained and the thickness, rather than the area of the deposit layer had been substantially reduced. This suggests that the deposit removal process is better described as delamination than edge erosion.

STUDYING FUEL INJECTOR HOLE DEPOSITS IN A FLEET OF EURO 5 VEHICLES

Experimental

Vehicle Selection

Vehicles were chosen for this study, based on the following criteria:

- Euro 5 emissions compliant - therefore all are fitted with modern common rail engines and DPFs;
- Represent 5 of the most popular European marques with read across to other vehicle types through common engine platforms;
- Represent a range of vehicle segments.

Table 3. Comparison of vehicles used in this study

Vehicle	OEM	Engine Capacity	Compression ratio	Output	Vehicle Segment
1	A	2.0L	16.5:1	170 PS	D
2	B	1.6L	16.5:1	105 PS	D
3	C	1.5L	15.2:1	110 PS	J - SUV
4	D	1.3L	16.8:1	95 PS	C
5	E	1.6L	16.0:1	115 PS	M - MPV

Test Fluids

CEC Reference RF-79-07 (batch 7) fuel was used throughout the Chassis Dynamometer (CD) testing. This fuel was selected to future-proof the results obtained; though the fuel used in the previously described static engine test was representative of a "real world", refinery sourced fuel, by definition it is not a perpetuated fuel composition and will vary in time due to changes in refinery feedstock and market conditions. The CEC Reference RF-79-07 fuel composition will remain relatively constant driven by the requirement to adhere to the fuel's specification and this in turn will allow comparison of this work with future studies. Furthermore RF-79-07 has the relevance of being specified in the industry standard CEC F-98-08 nozzle fouling test.

A novel fuel-borne detergent (same chemistry and concentration as per the engine test discussed earlier) was added to the clean-up fuel, as well as the stabilisation/run-in fuel.

1 mg/kg zinc (neodecanoate counter-ion) was added to the dirty-up and clean-up fuels as specified in the CEC test. Concentrations of zinc were confirmed by ICP-AES.

Table 4. Particulars of the test fuels for chassis dynamometer test

Fuel	Base Fuel	Target Zn Concentration (mg/kg)	Measured Zinc Concentration (mg/kg)	Novel Detergent Package
Stabilisation	CEC DF-79-07 (Batch 7)	0	0	x
Dirty-Up		1.00	0.85-0.95	
Clean-Up		1.00	0.95	x

Tank Fill Intervals

As the CEC F-98-08 test clean up phase results were plotted at intervals relevant to the tank capacity of the donor vehicle a comparison of the fuel consumption and tank capacity of the CD test fleet was completed to show if a similar data interval was applicable for the data obtained - see Table 5.

Table 5. Comparison of fuel tank capacity and fuel consumption

Vehicle	OEM	Tank Capacity (l)	Fuel Consumption (l/hr – in this test)	Fuel Consumed in 4 hrs (l)
1	A	65	16.1	64.6
2	B	70	12.6	50.6
3	C	55	12.5	50.0
4	D	56	10.0	39.8
5	E	70	12.6	50.3
Mean		63.2	12.8	51.1

The fill levels at which drivers refill their fuel tanks vary, but Table 5 shows that for this test cycle and fleet, the 4 hour interval used to present data as "a tank fill" is appropriate as the average data show that a 5 hour interval would exceed the fleet average tank capacity.

Test Cycle

Vehicle testing was completed on a CD using a minor modification of a previously published [2] test cycle. The method combines high fouling operating conditions with pro-fouling fuels to give measureable and repeatable fouling and clean-up evaluation within a 36 hour test. The legitimacy of test methods designed to simulate injector nozzle fouling occurring in the field are often challenged due to their tendency to operate at loads (severity) exceeding those normally experienced in the field, e.g. the aforementioned CEC DW10B test, [1]. The Shell method maintains a representation of real world driving by incorporating >50% duration of the test drive cycle at typical motorway road loads.

Contextualisation of Test Cycle Severity

Equivalent uphill gradients for the test method conditions are given to contextualize test severity.

Table 6. Test cycle condition split and equivalent fleet average gradients of test conditions

Stage	Percentage time spent at condition	Equivalent gradient for fleet average (°)
Maximum Accelerator Pedal Position (APP) for power measurement	1.1	6.4
Road load	50	0
80% load	47	4.7
Coast down & Transients between conditions	1.9	Various negative and positive

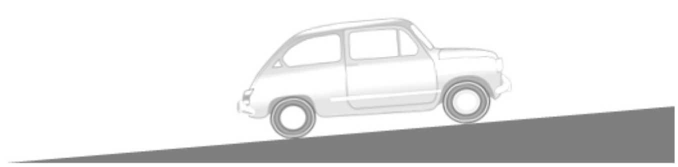

Figure 9. Illustration of gradient equivalent to 80% load condition for fleet average.

The illustration in Figure 9 shows that the gradient equivalent to load the 'fleet average vehicle' up to 80% at the defined road speeds would not be overly severe and could be encountered and exceeded by drivers on a regular basis. Even the full load condition would not represent a climb too steep to be found in normal driving. Full load conditions are also experienced whenever maximum accelerator pedal position is employed in everyday driving, for example when accelerating to join a highway or during overtaking.

The chart below shows that although the CD test cycle used here operated at a higher engine speed, the overall engine load was considerably less than the industry standard CEC F-98-08 nozzle fouling test.

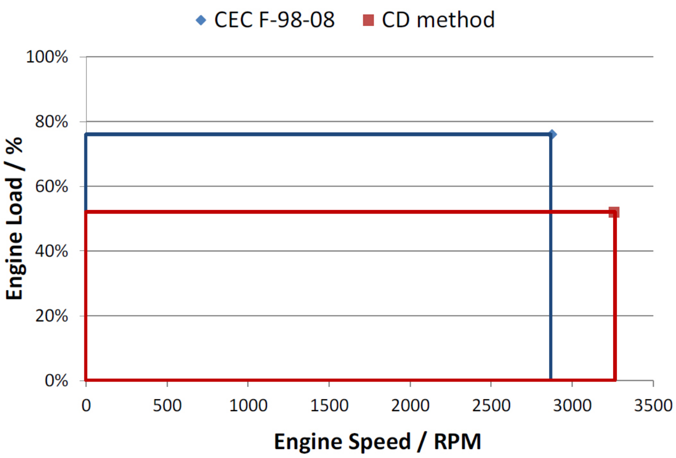

Figure 10. Comparison of the static engine and CD test method severity.

Test Procedure

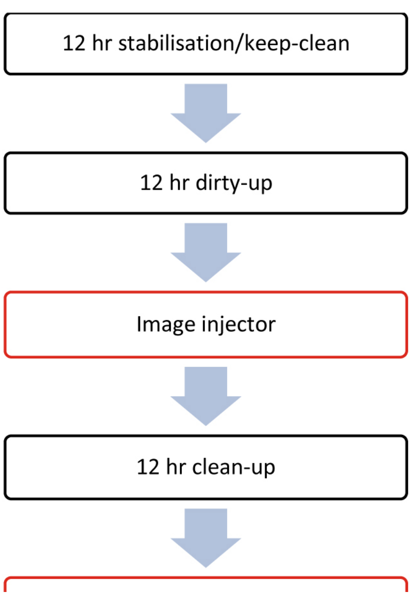

Figure 11. Test protocol for studying fuel injector hole deposits in a vehicle fleet.

SEM Analysis

Injector preparations for analysis by SEM & EDX were completed with the same methodology as for the bench engine testing. Images were collected at 15 kV and EDX spectra collected for each injector.

Results from Study of Fuel Injector Hole Deposits in a Fleet of Euro 5 Vehicles

Individual Vehicle Results - Maximum Accelerator Pedal Position Measurements

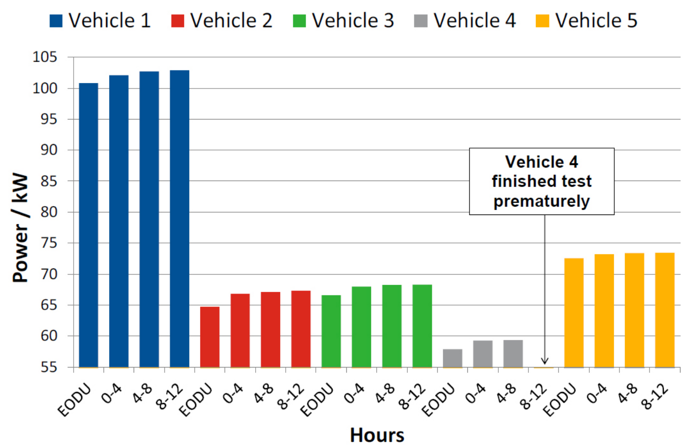

Figure 12. Change in absolute power (kW) at maximum Accelerator Pedal Position (APP) from End of Dirty UP (EODU) through clean up phase expressed in three x four hour intervals. Each interval is equivalent to a tank full of diesel containing the novel detergent (Table 4).

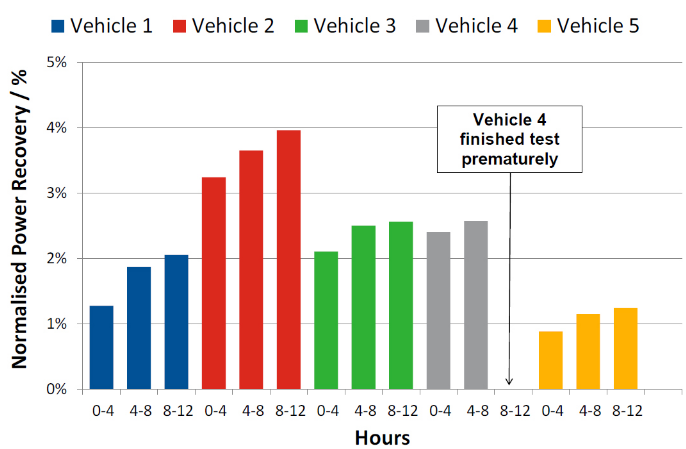

Figure 13. Change in relative power over clean-up (% change from EODU). Each interval is equivalent to a tank full of diesel containing the novel detergent.

Fleet Average Results - Maximum APP Measurements

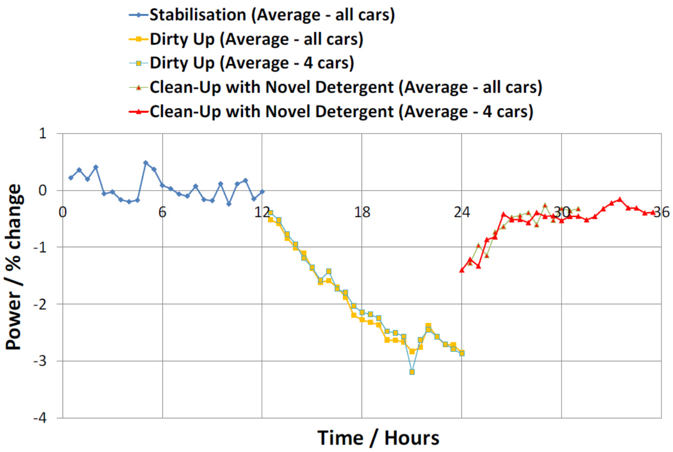

Figure 14. The fleet average % change in power at maximum APP. (Including a comparison of the effect of removing vehicle 4 from the fleet average which finished test early).

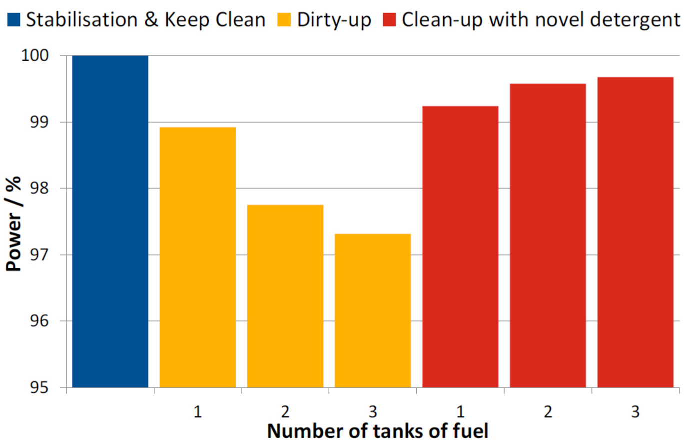

Figure 15. The fleet average % change in power at maximum APP normalised to the fleet average end of stabilisation (Including all vehicles in fleet average).

Fleet Average Results - BSFC Measurements at Maximum Power

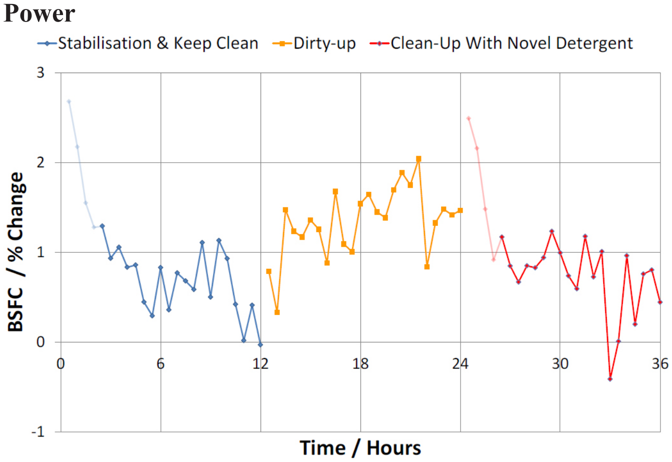

Figure 16. The fleet average % change in BSFC at maximum APP showing a tendency for worsening BSFC as deposits form and showing a tendency for BSFC to recover as deposits are removed. Faint lines show where BSFC was affected by vehicle thermal stabilisation.

SEM Images

Example Back Scattered Electron SEM images are shown below and the full set of images from the fleet can be found in the appendix.

Vehicle 1 - Hole 2

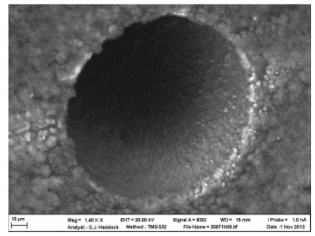

Figure 17. Example injector hole imaged after the dirty-up test phase. A deposit layer of irregular topography is evident within the injector hole.

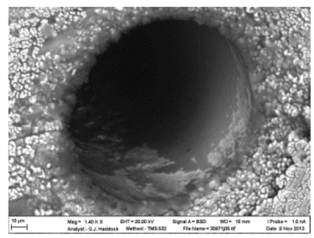

Figure 18. Same injector hole imaged after the clean-up test phase. The irregular deposit has been largely removed leaving a smooth texture. The thickness, rather than the area of the deposit layer has been substantially reduced

Vehicle 3 - Hole 2

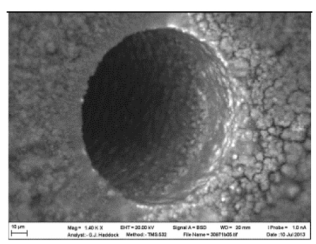

Figure 19. Example injector hole imaged after the dirty-up test phase. A heavy layer of irregular deposit is evident inside the injector hole.

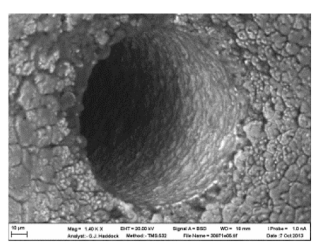

Figure 20. Same injector hole imaged after the clean-up test phase. The deposit has been largely removed by the action of the novel detergent, to reveal the underlying texture of the injector hole.

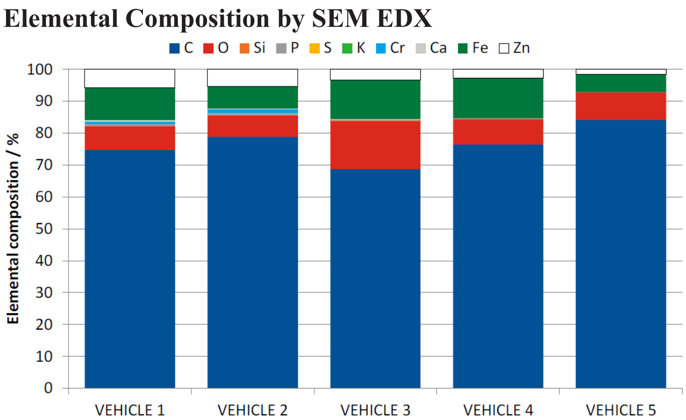

Figure 21. Average elemental composition of deposits analysed in-situ within fuel injector nozzle holes by EDX after dirty-up phase of test (weight % of analysed area - data tabulated in appendix). Note that the most abundant elements are C, O, Fe and Zn.

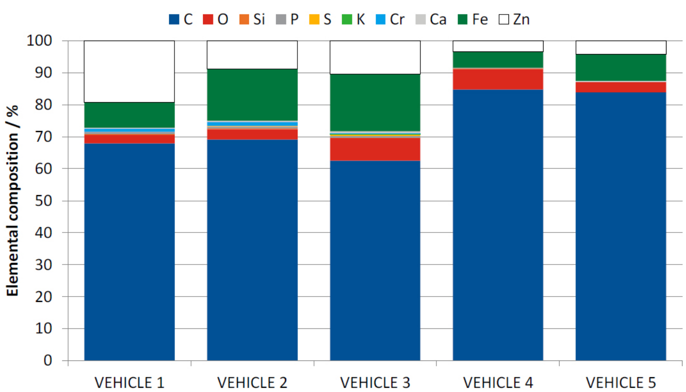

Figure 22. Average elemental composition of deposits analysed in-situ within fuel injector nozzle holes by EDX after clean-up phase of test (weight % of analysed area).

The tables and charts above show that the deposits formed during this study were predominantly made up of carbon, with other elements present in significant quantities.

- Zinc was present in all deposits measured. The majority of this would have come from the zinc neodecanoate dosed into the fuel as a pro-foulant, though a little may have come from burnt lubricant and pick up from vehicle fuel system materials.
- Calcium and Phosphorous were consistently present, albeit in small quantities, supporting the hypothesis that some elemental contamination of the deposits came from burnt lubricant.
- The proportion of carbon to metallic elements does not remain consistent between the dirty and cleaned injectors, though it is unclear as to the mechanism of any bias. Fe was detected in all samples, and is thought to be from the underlying injector metal substrate. The signal intensity may be linked to the deposit thickness.

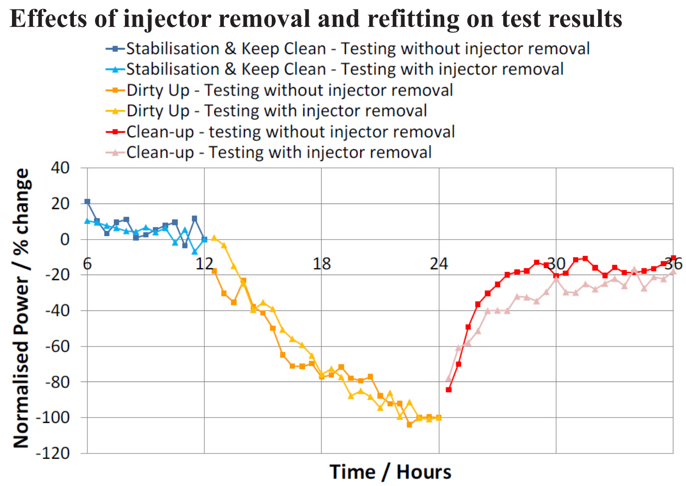

Figure 23. Change in power (%) in vehicle 1 - comparing power loss and recovery during previous work (squares, dark) with that of the current study (triangles).

Direct comparison between datasets for the current study and previous data [2] is possible by normalising the power change to the end of stabilisation. Figure 23 shows that the clean-up obtained when the injector was removed was slightly worse than in the continuous test during the initial phases of clean-up though the total percentage clean-up was comparable. This shows that removing and refitting the injector did not impose a positive bias on the clean-up result.

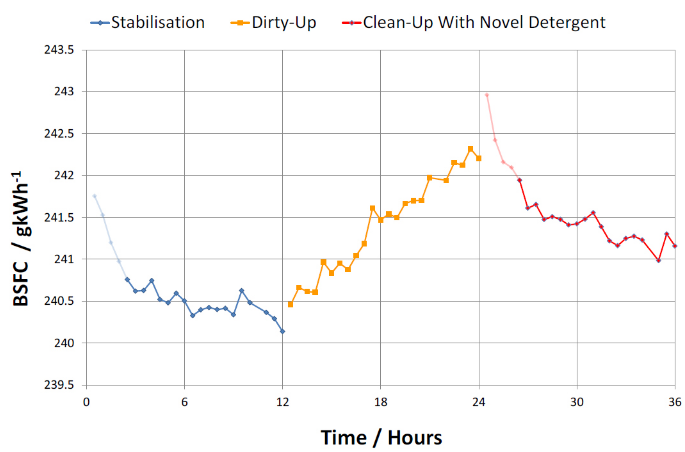

Figure 24. Change in BSFC at 80% load for Vehicle 1

Further investigation of the effect of interrupting the test for injector imaging entailed analysing the effect of this on BSFC. BSFC during the 80% load for this vehicle was chosen instead of the full load condition as it was less affected by DPF regeneration. Figure 24 shows that a comparable drop in BSFC was seen during the generation of the first few data points after both the initial start-up and the re-start following injector imaging. These data are illustrated in the figure by the data points with reduced colour intensity. This suggests that frictional losses in the vehicle engine and driveline reduce for the first two hours of running due to thermal stabilisation.

BSFC increases substantially as deposits form in vehicle 1 and decreases as deposits are removed. It should be noted that such a stark link between deposits and BSFC is not observed in all of the vehicles.

Summary of Vehicle Study

Injector nozzle hole deposits have been studied in a fleet of Euro 5 diesel passenger cars common in the European market with the aim of understanding the physical manifestation and performance effects of the deposits during formation and removal. Power loss was detected whilst running all 5 cars over the Shell CD test procedure with ZSD containing 1mg/kg zinc for 12 hours. SEM & EDX analysis confirmed that deposits form in the nozzle holes during this power loss period. Furthermore the deposit level in the nozzle holes was reduced after using the same dirty up fuel dosed with a novel detergent additive and this was accompanied by a recovery of the power lost during the dirty up phase in all 5 cars. Based on SEM images collected, the deposit removal process is better described as delamination than edge erosion (see Figure 17-Figure 18).

Elemental composition derived from EDX showed that the deposits formed consisted primarily of carbon with substantial levels of oxygen and zinc (likely to be from the fuel dopant) also being present. Iron was also detected and this is thought to be a signal from the nozzle substrate.

Average BSFC for the fleet of vehicles tended to increase during the dirty-up phase, showing that injector nozzle deposits could have an effect on both the amount of fuel delivered (affecting power output) and the combustion or thermodynamic efficiency (affecting BSFC). However, there was not a consistent effect across the fleet of vehicles.

Comparison with data generated during a test programme in which dirty up - clean-up was run without injector removal suggested that removal of a fuel injector for imaging by SEM & EDX in this programme did not impose a positive bias on the clean-up results attained.

Overview

This study has enabled the physical manifestation and performance effects of injector nozzle holes to be investigated in a derivative of the industry standard engine test and a fleet of cars representative of the European market. Key differences exist between the engine and vehicle work, including base fuel, test cycle intensity, test duration and use of fouling sensitised injector nozzles in the engine work. However key similarities also exist: both use zinc to accelerate fouling into viable test durations, employ high duty test cycles and modern common rail engines. A summary of the overall learning from the two halves of this study in terms of the key test parameters is given below.

Performance Effects of Deposits

Data collected from full load power measurements showed that power was lost as injector nozzle hole deposits formed in the engine test and in all five Euro 5 cars. The rate of power loss varied across the engine and vehicles and this range of sensitivity is attributed to engine specifics such as injector nozzle design and nozzle tip temperature. It is notable that all of the road vehicles exhibited some sensitivity to power loss which reinforces the relevance of the CEC DW10B test. The engine and all vehicles also responded to the detergent additive used in the clean-up phase, with the majority of the power lost during dirty up being returned in all cases in the short clean up test durations employed. This shows that high quality fuels can overcome deposit formation both in the severe industry standard test but also in real vehicles running more realistic driving cycles.

A lesser published effect of injector nozzle deposits observed here in the vehicle work is that on BSFC. As previously reported in [2], BSFC tends to worsen as deposits form and recover as deposits are removed. However this varies depending on individual vehicle and is not evident in the DW10B engine, suggesting the propensity of deposits to reduce combustion or thermodynamic efficiency required to result in a reduction in fuel efficiency could depend on nozzle design or other factors such as engine configuration. In the cases where efficiency is not affected while power is; it is postulated that the deposits restrict flow without affecting spray formation or injection timing to the extent that resulting effects on BSFC are easily detectable.

Engine out smoke or gaseous emissions could also have been affected by the formation and removal of deposits as suggested in [3, 4, 5], but these parameters were not measured in this study.

Physical Manifestation of Deposits

SEM images collected from the engine and vehicles at the end of the dirty up phase showed that deposits had formed inside the injector nozzle holes leading to power loss. Deposit formation varied across the engine and vehicle set with deposits appearing to be most severe in the engine test where the dirty up test duration and power loss was highest.

The mechanism for the effect of visible nozzle hole deposits on engine power is proposed to be a reduction in hydraulic efficiency of the nozzle holes. This is partly caused by the deposit layer reducing nozzle hole cross sectional area and partly from the visibly irregular deposit topography which will increase frictional flow loss effectively reducing the flow capacity of the nozzle. Because the injected fuel quantity is metered on a time (not volume) basis, reduced nozzle flow capacity will reduce the amount of fuel passing through the injector into the cylinder available for combustion. Irregular deposits could also disrupt the flow of fuel, therefore the fuel spray formation and atomisation, leading to reduced combustion efficiency or thermodynamic efficiency, resulting in increased emissions and reduced fuel efficiency and power.

During the clean-up phase, the deposits were removed gradually as a function of time and/or fuel used. This was reflected in the power recovery characteristic and in the intermediate injector SEM images in the engine test work. After 3 hours / 1 tank full of fuel equivalent, in the engine test, most of the power lost had been regained and the thickness, rather than the area of the deposit layer had been substantially reduced. This suggests that the deposit removal process is better described as delamination than edge erosion.

Deposits outside of the nozzle hole increased with engine run time and did not decrease during the clean-up phase. This is because these deposits do not come into direct contact with the liquid fuel and are therefore dominated by the gross combustion conditions in the engine.

EDX spectra used to estimate the elemental composition of deposits in the nozzle surface (vehicle tests only) showed that deposits were mostly carbon based, with contribution from metallic elements varying between vehicle, and dirty and clean injectors. The presence of P and Ca in some deposits suggested a link with burnt lubricant. Fe was detected in all spectra at moderate levels and is attributed to the nozzle substrate rather than deposit.

CONCLUSIONS

A study linking the physical manifestation and performance effects of diesel injector nozzle hole deposits has been completed in an adaptation of the CEC DW10B engine test and in a fleet of Euro 5 cars using the Shell CD test method. From the work it can be concluded that:

- Diesel injector nozzle deposit formation can be detected via loss of power and in their visible appearance using SEM;
- Deposits can reduce the hydraulic efficiency of the nozzle by reducing the cross sectional flow area, increasing frictional flow loss and disrupting spray formation;
- Deposit removal using a novel fuel borne detergent can be detected via recovery of lost power and via visible appearance using SEM;
- Deposits are removed gradually and the removal process is better described as delamination than edge erosion.
- EDX spectra used to estimate the elemental composition of the nozzle hole deposits showed that they were formed mainly from carbon, oxygen and the zinc fuel contaminant.
- In some engine/vehicle types, a detrimental effect on BSFC tended to accompany injector nozzle hole deposit formation, this tended to be reversed as deposits were removed through the use of a novel fuel borne detergent;
- In this study, formation of deposits on the injector nozzle body exterior are not affected by the presence of a fuel borne detergent and do not affect engine power;
- A fleet of five common Euro 5 diesel passenger cars were all susceptible to deposit formation, reinforcing the relevance of the industry standard CEC DW10B nozzle fouling test;
- Novel fuel borne detergent used at premium fuel dose rates is effective in removing accumulated deposits in the equivalent of a few tanks of fuel.

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APPENDIX

Table 7. Particulars of the CEC F-98-08 (DW10B) test cycle followed during the initial phase of this study

step	duration (minutes)	engine speed (rpm) +/- 20	load (%)	torque (Nm) +/-5
1	2	1750	20	62
2	7	3000	60	173
3	2	1750	20	62
4	7	3500	80	212
5	2	1750	20	62
6	10	4000	100	
7	2	1250	10	25
8	7	3000	100	
9	2	1250	10	25
10	10	2000	100	
11	2	1250	10	25
12	7	4000	100	
	∑ = 1 hour	Weighted average engine speed = 2875 rev/min	Weighted average engine load = 76%	

ANALYSIS OF FUEL INJECTOR HOLE DEPOSITS BY SEM & EDX

Scanning electron microscopy (SEM) is a non-destructive technique in which a primary electron beam penetrates a few hundred nanometres into the sample surface, and is either reflected from the sample (backscattered electron imaging), or causes emission of low energy secondary electrons from the sample (secondary electron imaging).

In neither of these operating modes is the structure of the sample changed, however it is possible that the electron beam may cause deposition of a very thin film of carbon onto the sample surface in the area of examination if hydrocarbons are present in the vacuum of the SEM chamber, but this would usually be observed by a darkening of the sample surface. To prevent this, and to improve the quality of images, before examination, the injectors were rinsed gently in n-heptane prior to, and after, a 24 hour period in a vacuum oven at 70°C to remove any residual diesel fuel. This procedure has been shown to be effective in removing loose deposits, which have been disturbed during injector removal, without affecting the deposits formed in operation.

Images were obtained using a large chamber SEM in variable pressure (VP) mode. VP mode allows non conducting samples, such as deposits on injectors, to be imaged and analysed without the need to sputter coat the sample with carbon or metal. Thus facilitating the removal and replacement of the injectors into the test engine/vehicle for continued operation.

Images were obtained using the Back Scattered electron Detector (BSD images) and the Variable Pressure Secondary Electron (VPSE) detector. BSD images show contrast that varies with the elemental composition of the specimen, such that elements of higher atomic number appear brighter in the image than those of lower atomic number. For images of fuel injectors, BSD images will therefore show carbon deposits as dark in comparison to the nozzle metal which will appear bright. VPSE images show the topography of a sample, but are more susceptible to charging if the sample is fully or partly non-conducting.

Analysis of the elemental composition of the nozzle tip deposits was completed by using Energy Dispersive X-ray (EDX) spectroscopy. Here, the incident electron beam displaces an electron from the lowest energy orbital of the atom in the deposit, and is replaced by an electron from a higher energy orbit, with associated X-rays emitted. Depending on the atomic number of the element; one, two or three X-ray energies are associated to it, corresponding to the K, L and M orbits and this enables the elements to be distinguished.

After calibration for the operating conditions used for analysis, EDX can provide a normalised value for weight or atomic percent of each element identified, but it should be noted that these values are only accurate for flat, polished samples, and hence can only be used as a general guideline for indicating if the elements are present in larger or smaller quantities, as well as mapping the distribution of each element.

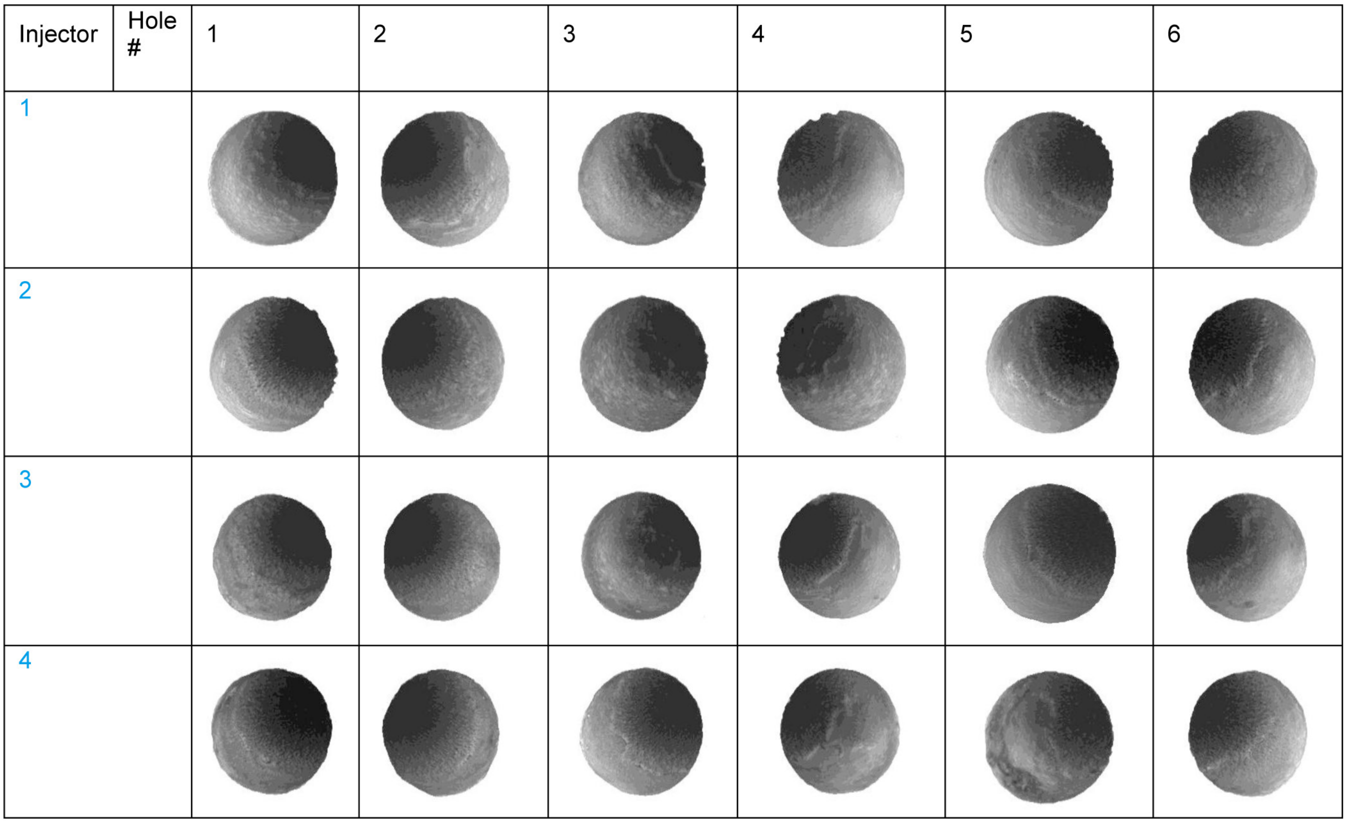

Figure 25. SEM images of injector nozzle deposits in the DW10B engine - after dirty-up

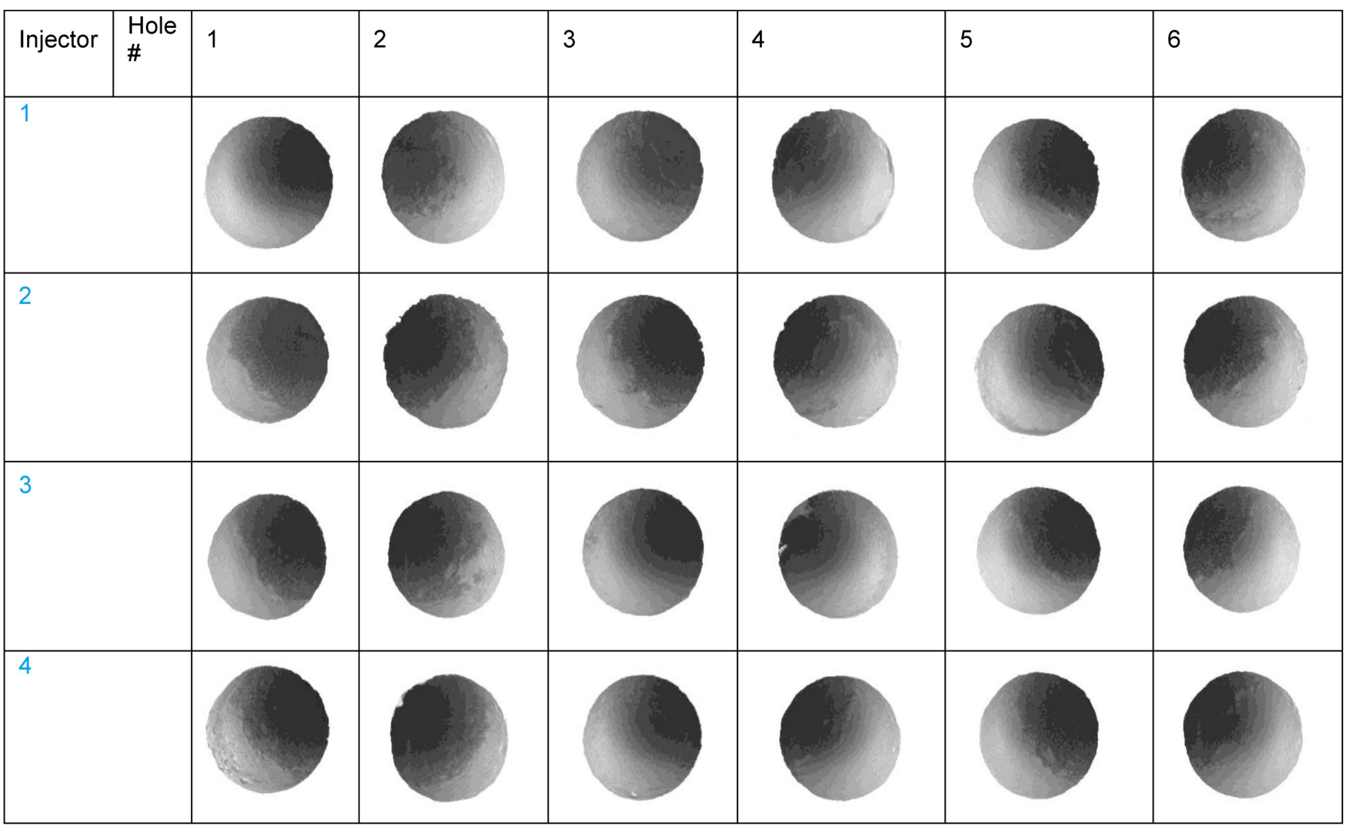

Figure 26. SEM images of injector nozzle deposits in the DW10B engine - after 3 hours/1-tank clean-up

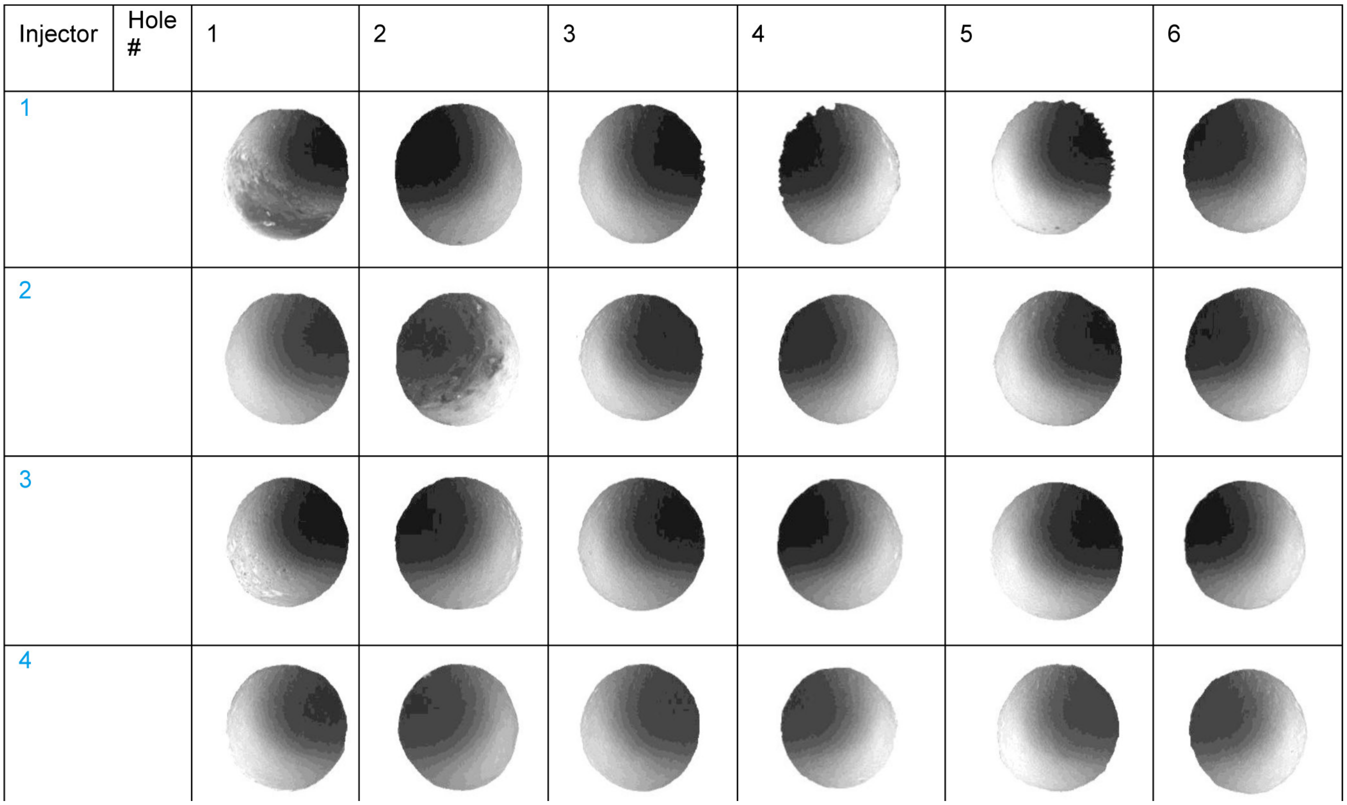

Figure 27. SEM images of injector nozzle deposits in the DW10B engine - at end of clean-up

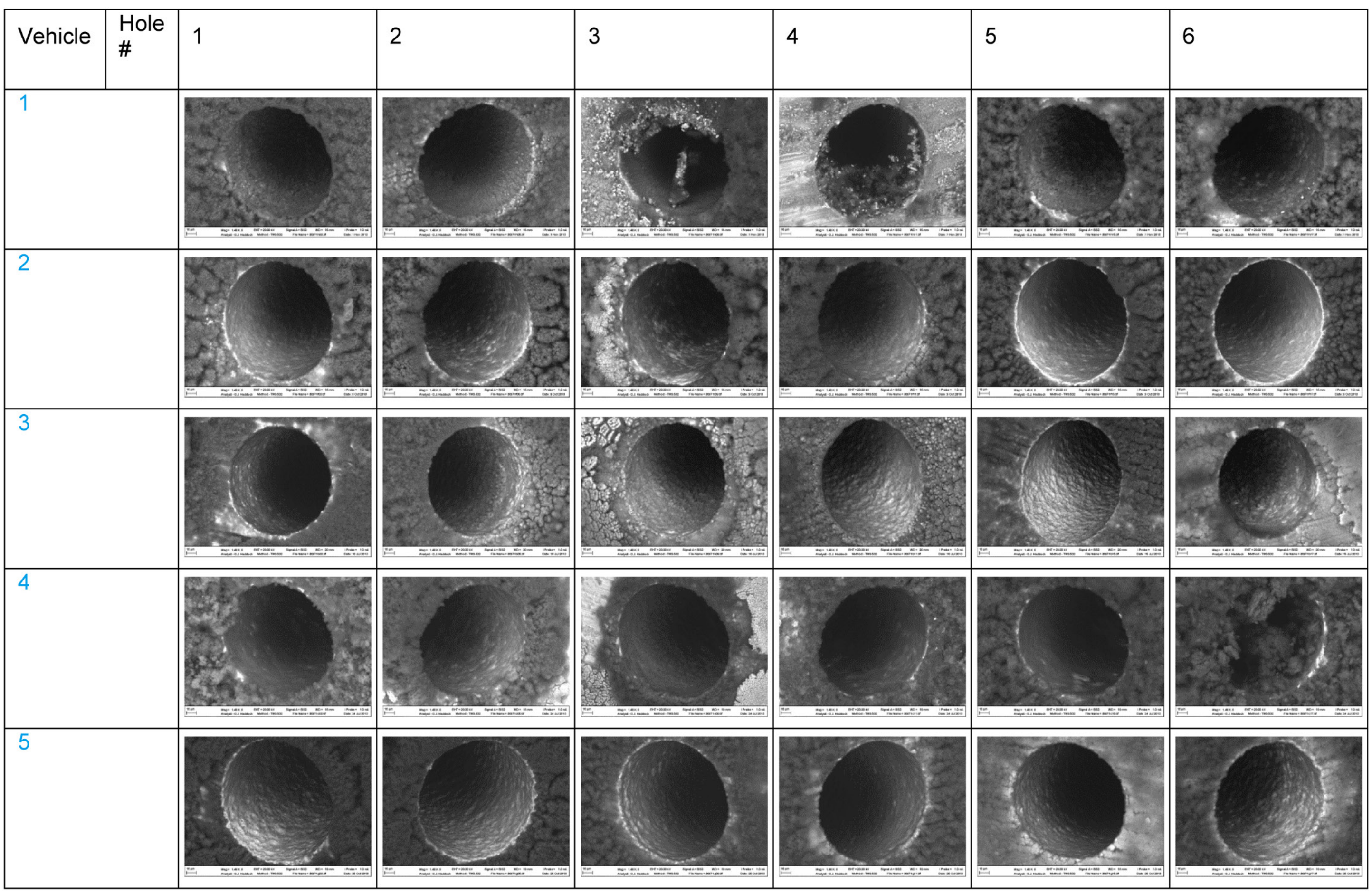

Figure 28. SEM images of injector nozzle deposits in the Euro5 vehicle fleet - after dirty-up (injector from cylinder 2, first 6 injector holes clockwise from datum)

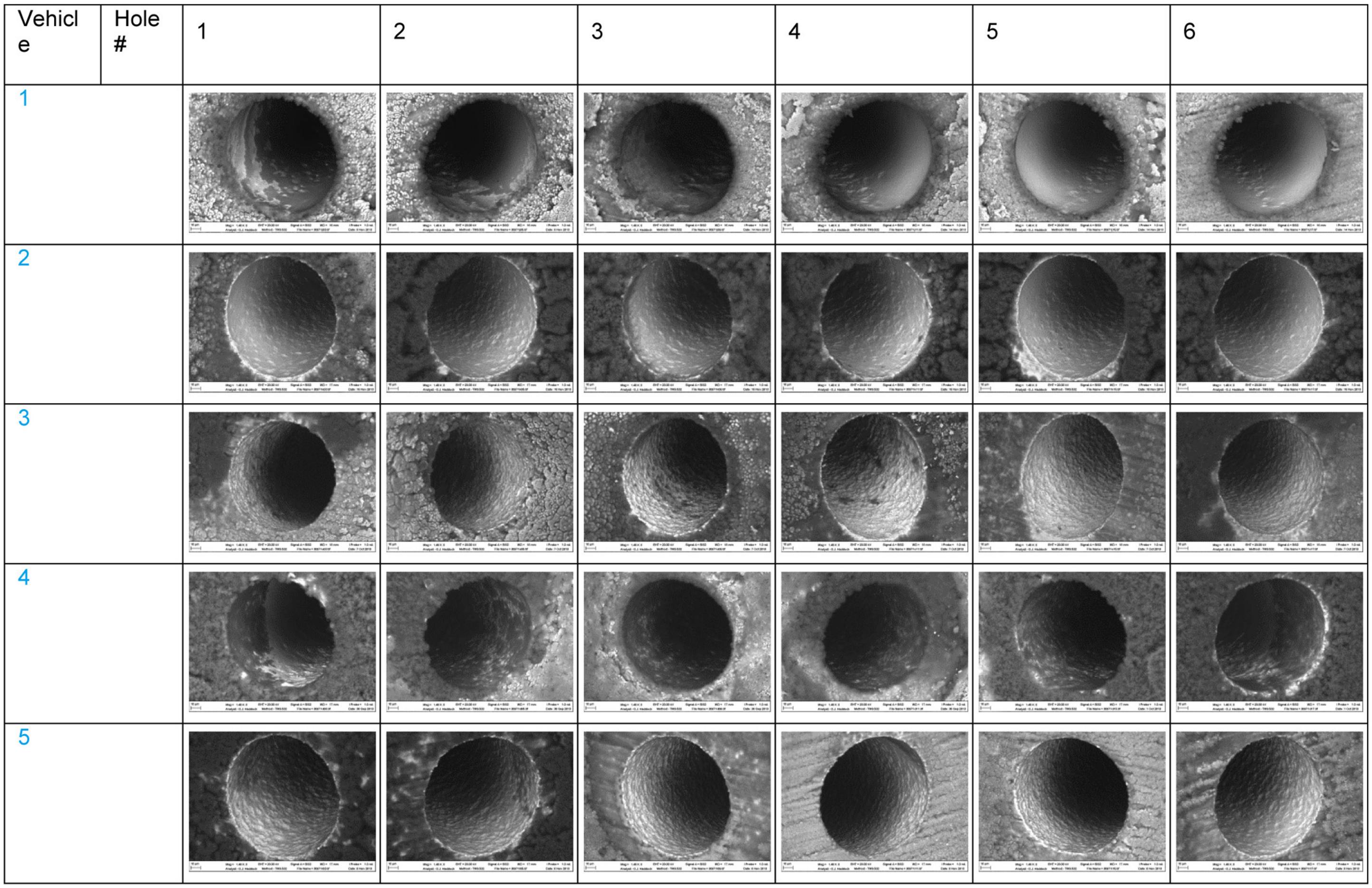

Figure 29. SEM images of injector nozzle deposits in the Euro5 vehicle fleet - after clean-up (injector from cylinder 2, first 6 injector holes clockwise from datum)

Table 8. Average elemental composition of deposits analysed in-situ within fuel injector nozzle holes by EDX after dirty-up phase of CD test (weight % of analysed area - 2 significant figures only).

Vehicle	C	O	Si	P	S	K	Cr	Ca	Fe	Zn
1	75	7.5		0.69			0.74	0.45	10	5.9
2	79	6.7		0.57	0.16		1.2	0.30	6.8	5.4
3	69	15	0.13	0.19				0.28	12	3.5
4	77	7.9		0.18					13	2.8
5	84	8.7							5.6	1.6

Table 9. Average elemental composition of deposits analysed in-situ within fuel injector nozzle holes by EDX after clean-up phase of test (weight % of analysed area).

Vehicle	C	O	Si	P	S	K	Cr	Ca	Fe	Zn
1	68	2.7	0.27	0.70			1.0	0.26	7.8	19
2	69	3.2	0.26	0.56	0.23		1.2	0.44	16	8.8
3	63	7.1	0.04	0.62	0.55	0.09	0.22	0.54	18	10
4	85	6.4	0.23	0.13					5.0	3.5
5	84	3.2						0.37	8.3	4.2