

Minimizing Diesel Particulate Filter Incombustibles by Using Ultra Low Ash - Zero Phosphorus Oil

James A. McGeehan
Chevron Lubricants

Wim Van Dam, Ken Nelson, Alex Boffa, and Kevin Carabell
Chevron Oronite Company LLC

Andrew Walker, Jon Caserta, and Raymond Conway
Johnson Matthey Emissions Control Technologies Division

ABSTRACT

Due to engine oil consumption, over 90% of the incombustibles in the diesel particulate filters (DPF) are derived from organometallic lubricant additives. These components are derived from calcium and magnesium detergents, zinc dithiophosphates (ZnDTP) and metal-containing oxidation inhibitors. They do not regenerate as they are non-volatile metals and salts. Consequently, the DPF has to be removed from the vehicle for cleaning.

Ashless oil could eliminate the need for cleaning. This study initially focused on development of an ashless oil, but eventually concluded that this oil could not meet the valve-train wear requirements of the API CJ-4, SN/ACEA E9 oil categories. However, a zero-phosphorus oil with no ZnDTP and an extremely low sulfated ash of 0.4% demonstrated that it could meet critical engine tests in API CJ-4/ACEA/SN.

The above oil, which has been optimized at 0.3% sulfated ash, has proven field performance in Cummins ISX with DPF using ultra low sulfur diesel (ULSD). This was verified by engine inspections and used oil analysis at 60,000 miles (97,000 km) oil drains. DPF cleaning determined at 95% confidence level that the 0.3% ash oil produced less incombustibles than a 1.0% ash API CJ-4 oil. Reducing the engine oil's ash by 70% resulted in a 78% reduction in DPF incombustibles. Consequently, the 0.3% ash oil will minimize DPF maintenance while also providing engine durability.

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INTRODUCTION

This paper is a sequel to the paper entitled "Extending the Boundaries of DPF with Ultra Low Ash Oil" (1), which described the development and engine testing of an ultra-low ash - zero phosphorous oil. It demonstrated that this oil could meet the critical tests in API CJ-4/SN and ACEA. It was postulated that such oil would reduce incombustibles in the DPF, which has been used on all on-highway diesel engines in the U.S. since 2007. This current paper completes the study by reporting the field test inspections of Cummins ISX engines after 500,000 miles (804,500km) on the 0.3% ash-zero phosphorus oil. The DPF's were removed and shipped to Johnson Matthey for cleaning. The results of this work verified in the field that lowering the sulfated ash level in the engine oil produced a

corresponding reduction in the incombustibles contained in the DPF. This would allow extended cleaning intervals of the DPF and reduce maintenance costs.

Also included are results from Mack and Caterpillar multi-cylinder dynamometer tests which add to the substantial data base reported in the previous paper. This data will be reviewed for purposes of continuity. In combination, these papers document a potential approach to future engine oil development beyond Proposed Category-11 (PC-11) in 2016. It may be particularly useful in applications where frequent cleaning of the DPF is required. Since DPF's will be almost ubiquitous in the future, this type of oil could significantly reduce maintenance costs, while still meeting engine durability standards.

These findings of this study are presented in the following five sections:

- Reductions of Particulate Through Use of DPF
- Ultra-Low Ash Oil Development
- Field Test Results and Engine Inspections of Cummins ISX Engines
- Comparison of DPF Incombustible Levels with Ultra-Ultra Low Ash oil versus conventional products

REDUCTION OF PARTICULATE THROUGH USE OF THE DPF

Despite recent improvements in regard to in-cylinder combustion, diesel engines cannot meet the U.S. Environmental Protection Agency (EPA) 2007 on-highway or the 2011 off-highway emission standards without DPFs. In order to meet the U.S. 2010, Japan 2010 and Europe 2013 emission standards for on-highway vehicles, the majority of truck manufacturers have selected a DPFs-SCR-urea system combined with a relatively low level of cooled EGR.

The DPF is comprised of an oxidation catalyst followed by a wall-flow particulate filter. The DPF traps the particulate matter and the oxidation catalyst oxidizes a portion of the engine's NO exhaust to generate NO_2 . This NO_2 results in thermal combustion of particulate matter at temperatures in the range of 250-350°C. This process is enhanced by the use of a "wash-coat" on the ceramic filter which releases NO_2 . The "wash-coat" enables a chemical reaction with continuous particulate removal.

Passive regeneration occurs in the DPF provided that the exhaust temperatures are sufficiently high for combustion of the particulate. If the temperature is not sufficiently high for regeneration, fuel is injected into the exhaust system at the outlet of the turbocharger when the delta pressure across the DPF is too high. This situation occurs generally in engines over 10 liters in which thermal combustion occurs in DPF at temperatures of 600°C (this is analogous to cleaning your oven). In passenger car diesels, there is post-injection of fuel into the cylinder during the exhaust event. This increases the exhaust temperature to produce "thermal combustion" in DPF. (Figure 1).

Due to engine oil consumption, over 90% of the incombustibles in the diesel particulate filters (DPF) are derived from organometallic lubricant additives. These components are derived from calcium and magnesium detergents, zinc dithiophosphates (ZnDTP) and metal-containing oxidation inhibitors. They do not regenerate as they are non-volatile metals and salts. Consequently, the DPF has to be removed from the vehicle for cleaning. [1, 2, 3, 4, 5, 6, 7, 8]

To remove the incombustibles, maximize the interval between DPF cleanings, it was recommended that the fresh oil sulfated ash be limited to 1.0% in the API CJ-4, ACEA E6/E9 and JASO

DH-2 oil categories. In addition, there are limits on fresh oil phosphorus, sulfur and volatility, although these limits vary according to the oil category. (Table 1)

Table 1. Comparison of API CJ-4 to ACEA E6 and JASO DH-2 chemical limits.

Oil Category	ACEA E6	API CJ-4	JASO DH-2
% Sulfated Ash	1.0	1.0	1.0
% Phosphorus	0.08	0.12	0.12
% Sulfur	0.3	0.4	0.5
% Volatility	13	13	18

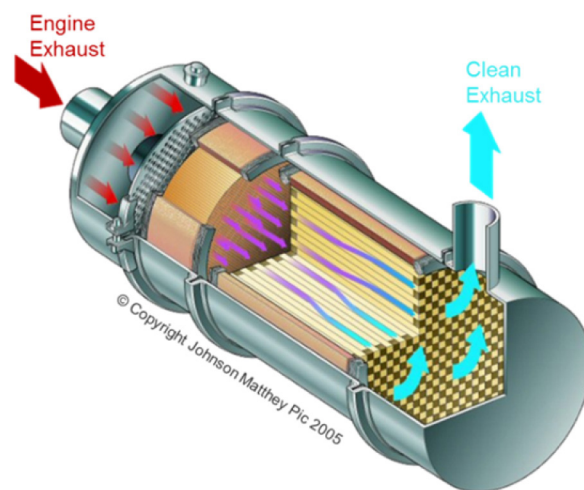


Figure 1. Passive DPF shown with wall-flow filter substrate.

DEVELOPMENT OF ULTRA-LOW ASH OIL

The initial intent of this research program was to develop an ashless oil which could eliminate the need for cleaning DPF's. This would require eliminating the greatest contributors to sulfated ash-detergents and ZnDTP, then evaluating these oils in the API CJ-4 engine and bench tests. This was first done by designing a matrix of candidates from fully formulated API CJ-4/ACEA E9 SAE 15W-40 oil with specific components removed. These oils were then tested for valve train wear in the Cummins ISB. As previously reported, this study demonstrated that a 0.2% ash-zero phosphorus oil could pass the Cummins ISB for valve-train wear, but had failing results in subsequent tests: Mack T-12; Cummins ISM; and GM gasoline test Sequence IIIG. [1] (See Table A-1 and A-2.)

Consequently, the above oil was boosted with antioxidant to compensate for the loss of ZnDTP, and a matrix of five antiwear additives were evaluated in the GM gasoline Sequence IIIG test. Four oils passed the test. The oil with the best antiwear film based on X-ray Photoelectron Spectroscopy (XPS) and Ar-ion etching, was a 0.4% ash-zero phosphorus oil. [1] (See Tables A-3)

This 0.4% ash-zero phosphorus was selected for further testing, and as previously reported (1) passed the following engine tests: VW TDi; (piston deposits); Cummins ISM (wear, sludge, filter delta P); GM Sequence IIIG (cam and tappet wear, viscosity increase and deposits); Nissan IVA (cam wear); and the Sequence VIII (copper-lead bearing corrosion). In bench tests, the oil passed the Ball Rust Test, but had failing results in the High Temperature Corrosion Bench Test and the ACEA AK6 seal test. (See Table 2 and Figures 2, 3, 4, 5).

Table 2. 0.4% Ash - 0% phosphorus - summary of engine tests (field test oil).

Oil Description	0.4% Ash – 0% Phosphorus SAE 15W-40 TBN ASTM D2896 – 7.0 TBN ASTM D4739 – 4.0	
Test	Result	Limit
Cummins ISM	Pass	(Max.-Anchor-Min.)
Crosshead Wear (mg)	4.9	7.1 – 5.7 – 4.3
Injector Screw Wear (mg)	20.8	49 – 27 – 16
Filter ΔP (kPa)	9.0	19 – 13 – 7
Sludge	9.3	8.7 – 9.0 – 9.3
Top Ring Wear (mg)	11.5	100 Max.
Merits	1,647	1,000
Sequence IIIG	Pass	
% Viscosity Increase	25	<150
Wear ACLW (μm)	34	60 Max.
WPD (Piston Deposits)	8.33	3.5 Min.
Piston Skirt Varnish	9.88	Report
Oil Consumption	2.13	Report
Sequence IVA (SN)	Pass	
Cam Wear (μm)	65	90
VW TDi	Pass	
Piston Deposits	63	Ref. Oils
Sequence VIII	Pass	
Bearing Wt Loss (mg)	18.3	26
Ball Rust Test	Pass	
Grey Value	120	100
HTCBT	Fail	
Lead (ppm)	1	120
Copper (ppm)	194	20
ACEA Seals	Fail	
AK6-Tensile Strength (% Change)	-56	-50

New data in development. Since first reporting the above results new data has been added to this study with the 0.4% ash oil. Table 3 shows test results which were generated subsequent to the previous publication. Due to the failing results in HTCBT for copper corrosion, a very low level copper inhibitor was added to the formulation and this achieved passing results in the bench test. This was then followed with passing results in these engine tests: Mack T-12, 300 hour test (oxidation defined by lead increase, liner-ring wear and oil consumption); Caterpillar C13, 500 hour test (piston deposit and oil consumption) and Caterpillar 1N, 252 hours (piston deposits and oil consumption). See Figures 6-7.

Table 3. NEW ENGINE DATA 0.4% Ash - 0% phosphorus - summary of engine tests.

Oil Description (Minor Modification to Pass HCBT)	0.4% Ash – 0% Phosphorus SAE 15W-40 TBN ASTM D2896 – 7.0 TBN ASTM D4739 – 4.0	
Test	Result	Limit
HTCBT	Pass	
Lead (ppm)	2	120
Copper (ppm)	20	20
Caterpillar 1N	Pass	
Deposits IN	284.1	286.2
Top Groove Fill (%)	13	20
Top Land Carbon (%)	1.0	3
Oil Consumption (g/kW-Hr)	0.13	0.5
Mack T-12	Pass	(Max.-Anchor-Min.)
Liner Wear (μm)	10.5	24 – 20 – 12
Top Ring Wear (mg)	85	150 – 70 – 35
Lead 0-300 (ppm)	22	35 – 25 – 10
Lead 250-300 (ppm)	4	15 – 10 – 0
Oil Consumption (g/Hr)	50	85 – 65 – 50
Merits	1,474	1,000
Caterpillar C-13	Pass	(Max.-Anchor-Min.)
Oil Consumption (g/Hr)	27	31 – 25 – 10
Top Groove	45.46	53 – 46 – 30
Top Land Carbon	25	35 – 30 – 15
Second Ring Deposits	17.5	33 – 22 – 5
Merits	1,011	1,000



Figure 2. Passing results in the Sequence IIIG cam and lifters (0.4% ash - 0% phosphorus - SAE 15W-40 oil).

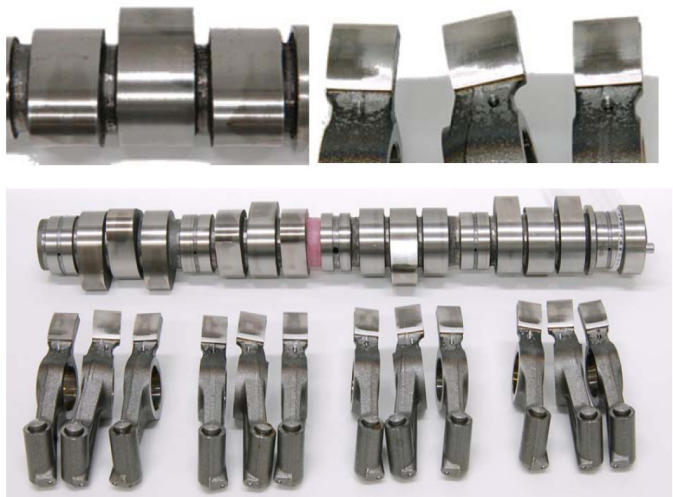


Figure 3. Passing results in the Sequence IVA cam and followers (0.4% ash - 0% phosphorus - SAE 15W-40 oil).



Figure 4. Passing results of the 0.4% ash - 0% phosphorus - SAE 15W-40 oil Cummins ISM injector screws.



Figure 5. Passing results in the VW TDi deposit results piston/undercrown (0.4% ash - 0% phosphorus - SAE 15W-40 oil).



Figure 6. Passing results in Caterpillar IN (0.4% ash - 0% phosphorus - SAE 15W-40 oil).



Figure 7. Passing results in Caterpillar C13 (0.4% ash - 0% phosphorus - SAE 15W-40 oil).

Table 4. 0.3% Ash - 0% phosphorus - summary of engine tests.

Oil Description	0.3% Ash – 0% Phosphorus SAE 15W-40* TBN ASTM D2896 – 6.8 TBN ASTM D4739 – 4.0	
Test	Result	Limit
Cummins ISM	Pass (CJ-4)	(Max.-Anchor-Min.)
Crosshead Wear (mg)	4.6	7.1 – 5.7 – 4.3
Injector Screw Wear (mg)	47.1	49 – 27 – 16
Filter ΔP (kPa)	1.0	19 – 13 – 7
Sludge	8.9	8.7 – 9.0 – 9.3
Top Ring Wear (mg)	45.8	100 Max.
Merits	1,055	1,000
HTCBT (Corrosion)	Pass	
Copper (ppm) Increase	19	20 Max.
Lead (ppm) Increase	2	120 Max.
Copper Strip Rating	2C	3 Max.
Sequence IVA (SM)	Fail	
Cam Wear (μm)	139	90 Max.
API CJ-4 Seals	Pass	
Nitrile	Pass	
Polyacrylate	Pass	
Fluoroelastomer	Fail *	Marginal
Silicone	Pass	
Vamac	Pass	
Cummins Field Test	Pass	Pass

As previously reported, the 0.4% ash oil was successfully tested in Cummins ISX engines in the field but the trucks were sold prior to DPF cleaning. [1]. However, based on the successful test results of the 0.4% ash - zero phosphorus oil, further development was undertaken. It was decided to