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Effectiveness of Different Aftertreatment Systems in PM Reduction of Non-Road Diesel Engines

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Exhaust emissions of all kind of diesel engines are to be drastically reduced in the near future both in the EU, Japan, and the US. Of the pollutants, particulate matter (PM) and the oxides of nitrogen (NO_x) form the main challenge for diesel engine development. Thanks to the upcoming strict legislation, future engine models will emit considerably less exhaust pollutants than the older engines.

Nevertheless, it is widely accepted that effective exhaust aftertreatment systems must also be incorporated into the exhaust systems of modern non-road diesel engines in order to bring the engines in compliance with the emissions standards coming into force in the 2010s.

In the present study, different diesel particulate filters (DPFs) were studied in conjunction with modern non-road diesel engines, equipped with common-rail injection systems. The main objective of the study was to reduce exhaust emissions to such a low level that the engines would fulfill the demands of stringent current and future emissions legislation. Before the measurements, each filter was run in for three to six hours.

Engines of two different sizes were examined, one having a swept volume of 3.3 dm^3 and the other 7.4 dm^3. The smaller engine had a 2-valve cylinder head, whereas a 4-valve head was utilized in the bigger one. Several different DPFs were investigated, both from the viewpoint of their efficiency and regeneration temperature. NO_2 slip was also determined.

Additionally, an HC-SCR catalyst was studied with the smaller engine mainly for NO_x reduction. The ability of this catalyst to reduce particles was, however, also examined. The catalyst did reduce larger particles effectively while the reduction of nuclei-mode ones remained moderate.

It should be emphasized that the authors focused - and will focus - on diesel engine development to bring the engines in compliance with the future emissions legislation. The basic development of exhaust aftertreatment systems is not included in the business of the affiliations. Therefore, the results obtained from different PM reduction systems represent more a user aspect.

The results showed that there were large differences between the filters in the removal efficiency. In the larger 4-valve engine, the best DPF reached a reduction efficiency of 99.8 to 100% in three digits, whereas the efficiency of the poorest DPF ranged from 85.8 to 99.8% – fairly acceptable as such. For the worst DPF, the lowest value was recorded at 75% load at intermediate speed (Mode 6) and the highest result at 10% load at rated speed (Mode 4). The DPF with catalytic coating was not the best filter of the four studied DPFs.

In the smaller 2-valve engine, the poorest DPF reduced particles by an efficiency of 88.3 to 99.6%, the highest value being, again, recorded at low load at rated speed, or at Mode 4, and the lowest efficiency at high part load at intermediate speed, or at Mode 6. Two of the studied filters were almost equal in efficiency, since one showed 99.2 to 100% efficiencies and the other 99.5 to 99.8%. Both were, thus, very efficient. Altogether, three filters were investigated, one of them as two concept versions.

In each case above, the efficiencies were determined for the particle size category at which the engine showed the highest particle number without any aftertreatment system, i.e. under baseline conditions.

Despite Mode 4, the share of NO_2 within NO_x increased from below 5% to more than 20% in all filters studied with the 2-valve engine. At its highest, NO_2 formed almost 40% of the total NO_x downstream the DPF.

In the 4-valve engine, the NO_2 slip was only studied at Modes 3 and 7. Downstream the DPF, the share of NO_2 in NO_x varied here from 14 to 58% at Mode 7 and from 7 to 49% at Mode 3. One of the filters clearly differed from the others by being superior in this respect, since three filters showed NO_2 shares of 44 to 58% at those running modes. NO_2 was determined both upstream the DPF (after the DOC) and downstream the filter. In many cases, NO_2 seemed still to increase in the filter. It should be noted, however, that recordings from parallel tests were examined in many cases when comparing NO_x compositions up- and downstream the DPF.

The HC-SCR catalyst also proved efficient in reducing larger particles. At intermediate speed, efficiencies of 82 to 90% were recorded. At the smallest particle category, the particle reduction was, however, only 27 to 41% at this speed.

The results of the true DPFs were mainly in line with what had been reported previously. Bosteels and Searles (2002) say that most DPFs reach a collecting efficiency of 99% when looking at ultra-fines. A DPF consisting of a catalyst unit followed by an uncatalyzed cordierite filter had particle size based percent reduction values of above 90% at all particle sizes in Shah et al. (2007).

For comparison, Sasaki et al. (2006) have measured reductions by 60 to 80% with an oxidation catalyst within the nanoparticle size range in light-duty diesel trucks. In a heavy-duty engine, the nanoparticle number was lower and a maximum reduction of barely 50% was noticed within a very narrow particle size range. On the contrary, a catalyzed DPF was even here very effective for the reduction of both nuclei-mode and accumulation-mode particles.

In the present study, regeneration did not start until at temperatures of 320 °C to 420 °C depending on the filter. The recorded regenerating temperatures were so high that the duty cycle of a non-road machine does not necessarily achieve high enough loads to fully create the regeneration heat. Brooke (2008) proposes synthesis gas technology as an aid. The process uses DFO and air or exhaust gas to generate a mixture of hydrogen and carbon monoxide. This is very reactive and quite useful for cleaning DPFs. Amberla (2008), in turn, suggests partial open-type particulate filters (pDPF) as more suitable than DPFs for many applications.

As an application developer, we cannot be satisfied with the large variations in the efficiency of different filter brands. The NO_2 slip must also be generally reduced. Furthermore, regeneration ought to start at lower than the detected temperatures.

Amberla, A. (2008). Proventia Emission Control products and services. Oral presentation at a Seminar called “Engine Technology based on Sustainable Development”. Helsinki, Finland, March 27, 2008. Arranged by The Federation of Finnish Technology Industries. Ppt-slides available at http://www.teknologiateollisuus.fi/index.php?m=2&s=5&d=4&id=17754. (In Finnish.)

Bosteels, D. and Searles, R. A. (2002). Exhaust Emission Catalyst Technology. Platinum Metals Review, Vol. 46 (2002), No. 1, p. 27-36.

Brooke, L. (ed.) (2008). It’s a gas. AEI, Vol. 116, No. 4, p. 108-109.

Sasaki, S., Tonegawa, Y. and Nakajima, T. (2006). Measurement of Nanoparticles from Vehicles and Formation Factors. Review of Automotive Engineering, Vol. 27 (2006), p. 199-206.

Shah, S. D., Cocker III, D. R., Johnson, K. C., Lee, J. M., Soriano, B. L. and Miller, J. W. (2007). Reduction of Particulate Matter Emissions from Diesel Backup Generators Equipped with Four Different Exhaust Aftertreatment Devices. Environ. Sci. Technol., Vol. 41, p. 5070-5076.

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About the speaker:

Seppo Niemi,

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- Professor at the University of Vaasa (fixed-term public-service) and Principal Lecturer at Turku University of Applied Sciences, Finland
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Outline

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  - Fuels
  - Filters
  - HC-SCR catalyst
  - Test cycle
- ISO 8178 results
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- NO_2 slip
- HC-SCR performance
- Engine differences
- Comparisons
- Exhaust temperatures
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Objectives

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- To compare the efficiency of different diesel particulate filters (DPFs)
- To determine the PM removal efficiency of a HC-SCR catalyst
- We develop engines and applications, not filters or catalysts
  - User aspect!

Experimental setup: engines

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Engine	CR, 2-valve, EGR	CR, 4-valve, EGR
Bore	108 mm	108 mm
Stroke	120 mm	134 mm
Swept volume	3.3 dm^3	7.4 dm^3
Compression ratio	18.5	17.5
Rated power	75 kW at 2200 rpm	175 kW at 2200 rpm
Injection pump or system	Bosch Common-rail, 1400 bar	Bosch Common-rail, 1600 bar
Turbocharger	Schwitzer S100	Borg-Warner VGT
Intercooler	air-to-water	air-to-water

Experimental setup: fuels

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		CR, 2-valve, EGR, batch 1	CR, 2-valve, EGR, batch 2	CR, 4-valve, EGR, batch 1	CR, 4-valve, EGR, batch 2	CR, 4-valve, EGR, batch 3
Carbon	%	85.3	86	86.7	86.3	86.2
Hydrogen	%	13	13.4	13.1	13.3	13.4
Total aromatics	%	27	29.8	28.3	27.4	25.3
Monoaromatics	%	22.8	25.4	23.6	23.5	21.2
Di-aromatics	%	3.8	4	4.2	3.6	3.6
Tri-aromatics	%	0.5	0.4	0.5	0.4	0.5
Polyaromatics	%	4.3	4.4	4.7	4	4.1
Nitrogen	mg/kg	24	19	28	67	40
Sulfur	mg/kg	38	6	8	12	8
Cetane number		53.4	52.4	57.5	52.7	55.2
Ash, 775 °C	%	< 0.001	< 0.001	0.001	< 0.001	< 0.001
		Reference	**Filters 2 and 3**	**Reference**	**Filter 1**	**Filter 3**
		Filter 1	**Filter 1b**		**Filter 2**	**Filter 4**

Experimental setup: filters

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CR, 4-valve, EGR	Diameter	Precious metals	Concept
	mm	g/m^3	
Filter 1	286	350	DOC + DPF
Filter 2	286		DOC + DPF
Filter 3	286		DOC + DPF
Filter 4	286	880	DOC + cDPF

CR, 2-valve, EGR	Diameter	Concept
	mm	
Filter 1	190	DOC + DPF
Filter 2	190	DOC + DPF
Filter 3	230	DOC + DPF
Filter 1b	190	Filter 1 $^{w}/_{o}$ DOC

Experimental setup: HC-SCR catalyst

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- Cordierite monolith
  - Wash-coated by Al_2O_3 carrier, saturated by silver
  - 400 cpsi
- Five reduction cells, one oxidation cell

Experimental setup: ISO cycle

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Mode	Speed	Torque
#		%
1	Rated	100
2	Rated	75
3	Rated	50
4	Rated	10
5	Intermediate	100
6	Intermediate	75
7	Intermediate	50
8	Idle	0

ISO 8178 emissions results

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CR, 2-valve, EGR	Reference	Filter 1	Filter 2	Filter 3
NMHC+NOx	3.4	3.3	3.1	3.2
NOx	3.2	3.3	3.1	3.1
HC	0.23	0.012	0.010	0.005
CO	0.50	0.003	0.001	0.006
PM mass (calc.)	0.14	0.026	0.027	0.030
SFC	242	240	241	241

CR, 4-valve, EGR	Reference	Filter 1	Filter 2	Filter 3	Filter 4
NMHC+NOx	3.4	3.1	3.2	2.9	2.8
NOx	3.3	3.1	3.2	2.8	2.8
HC	0.11	0.01	0.00	0.01	0.01
CO	0.43	0.00	0.00	0.10	0.00
PM mass (calc.)	0.15	0.030	0.028	0.026	0.026
SFC	230	232	231	233	235

Filter performance, 1/6

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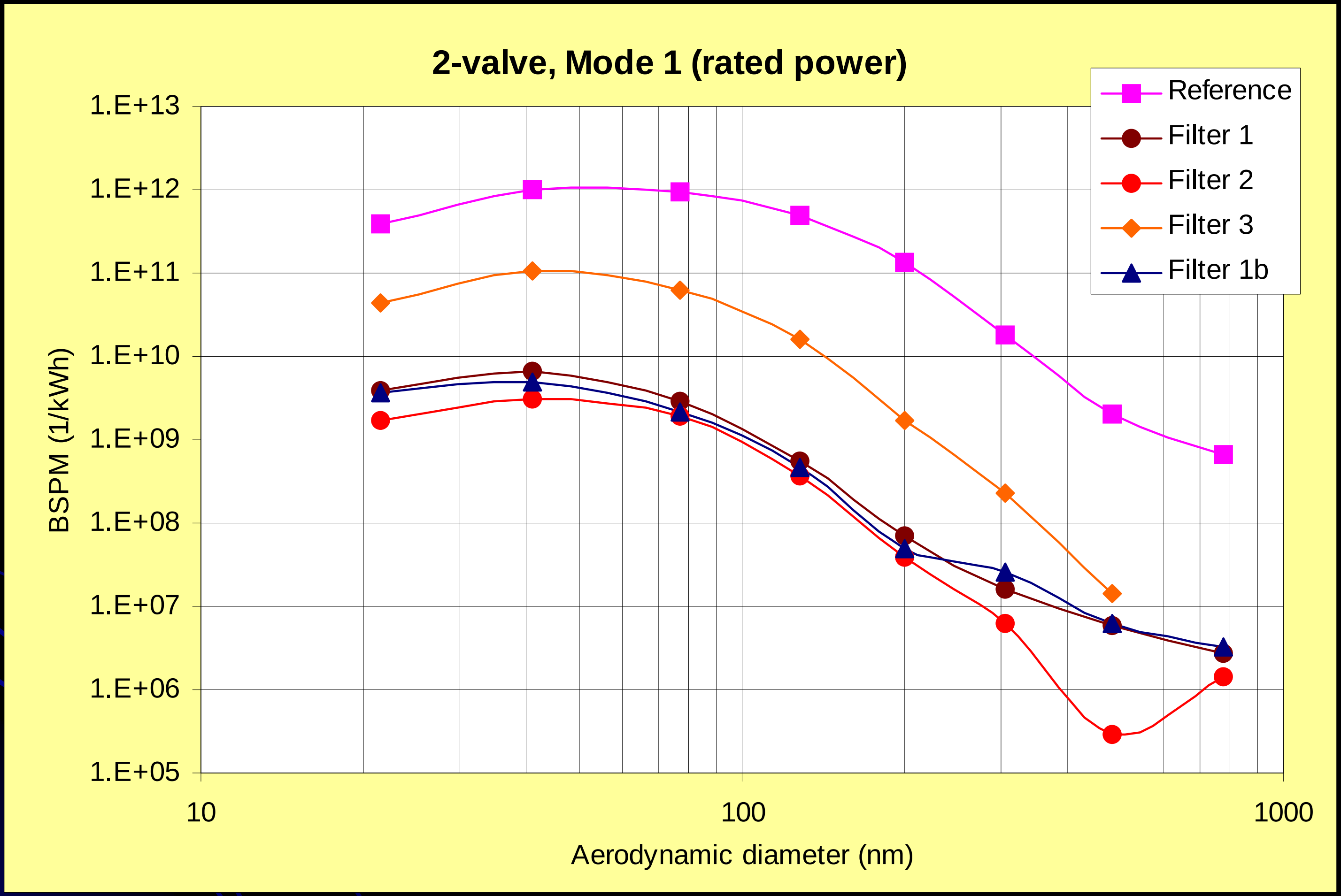

Filter performance, 2/6

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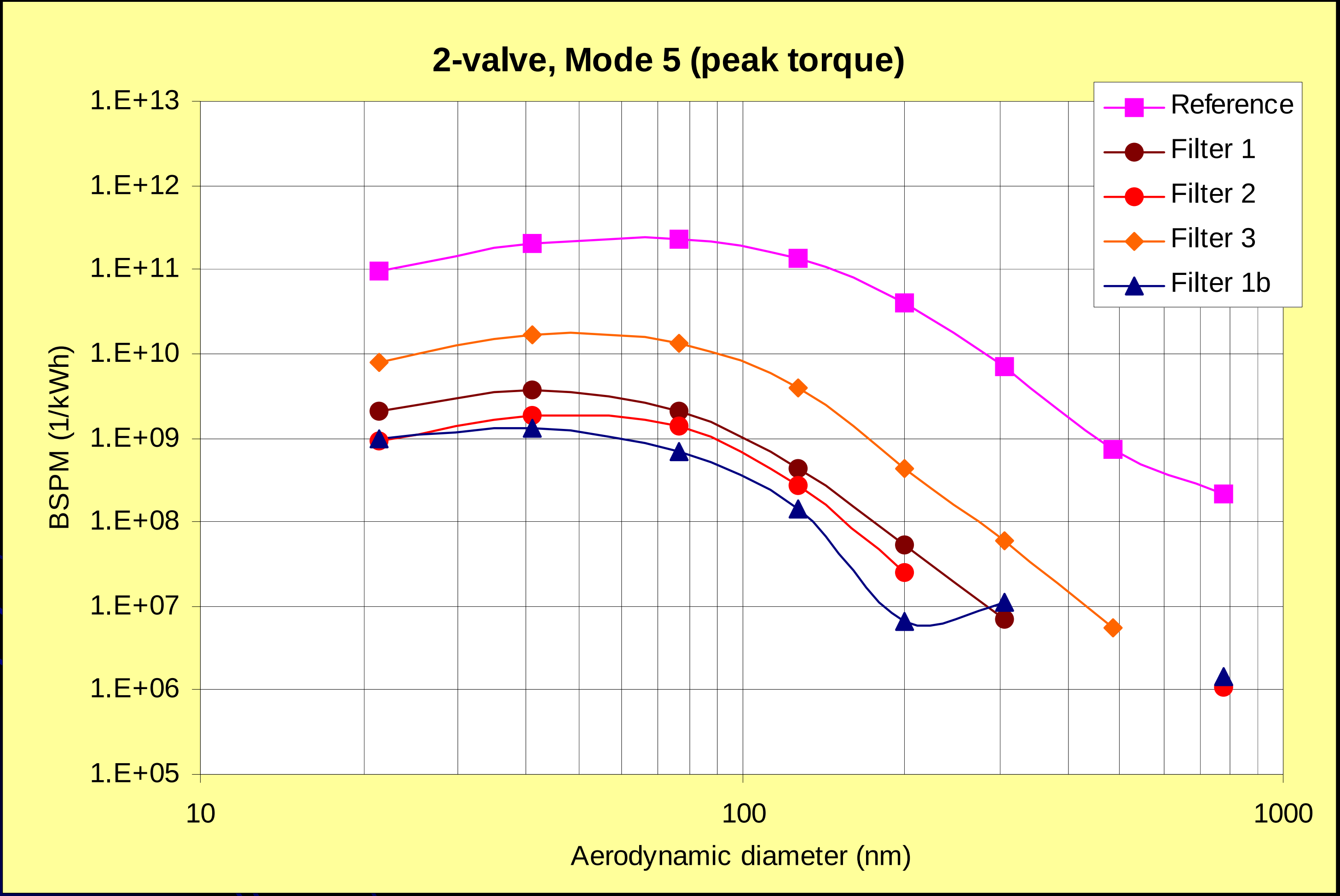

Filter performance, 3/6

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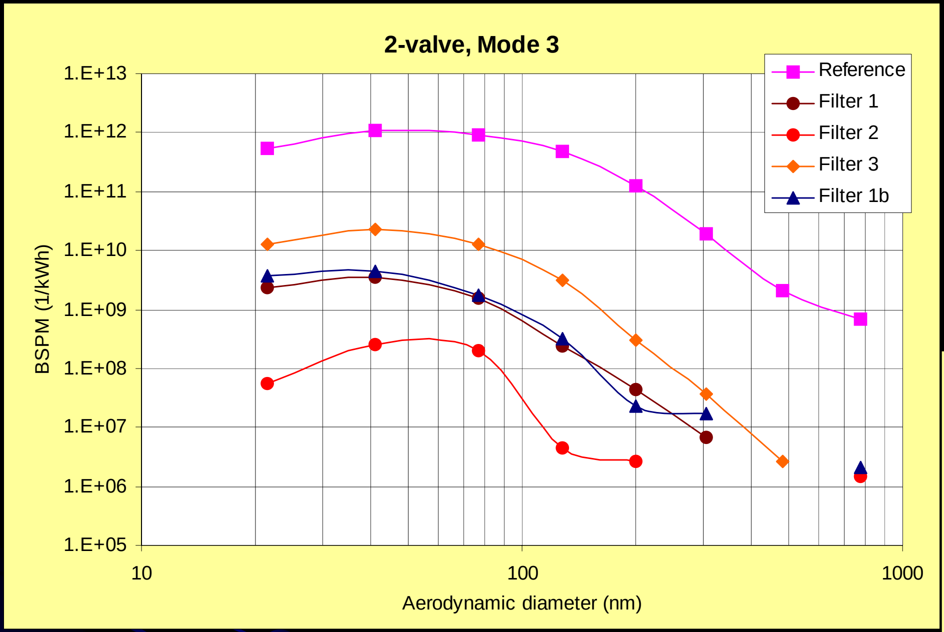

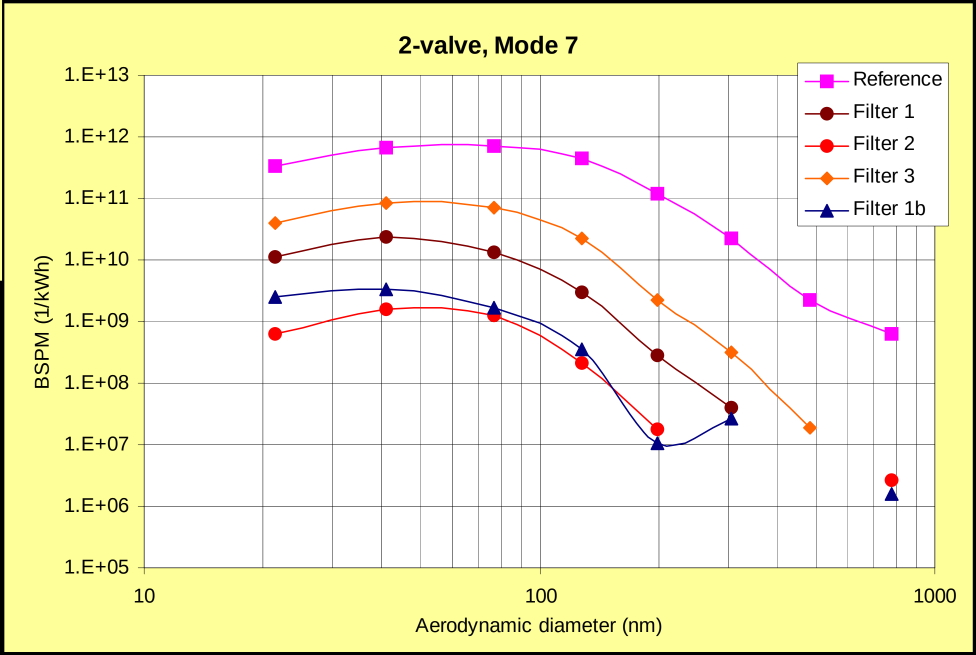

Filter performance, 4/6

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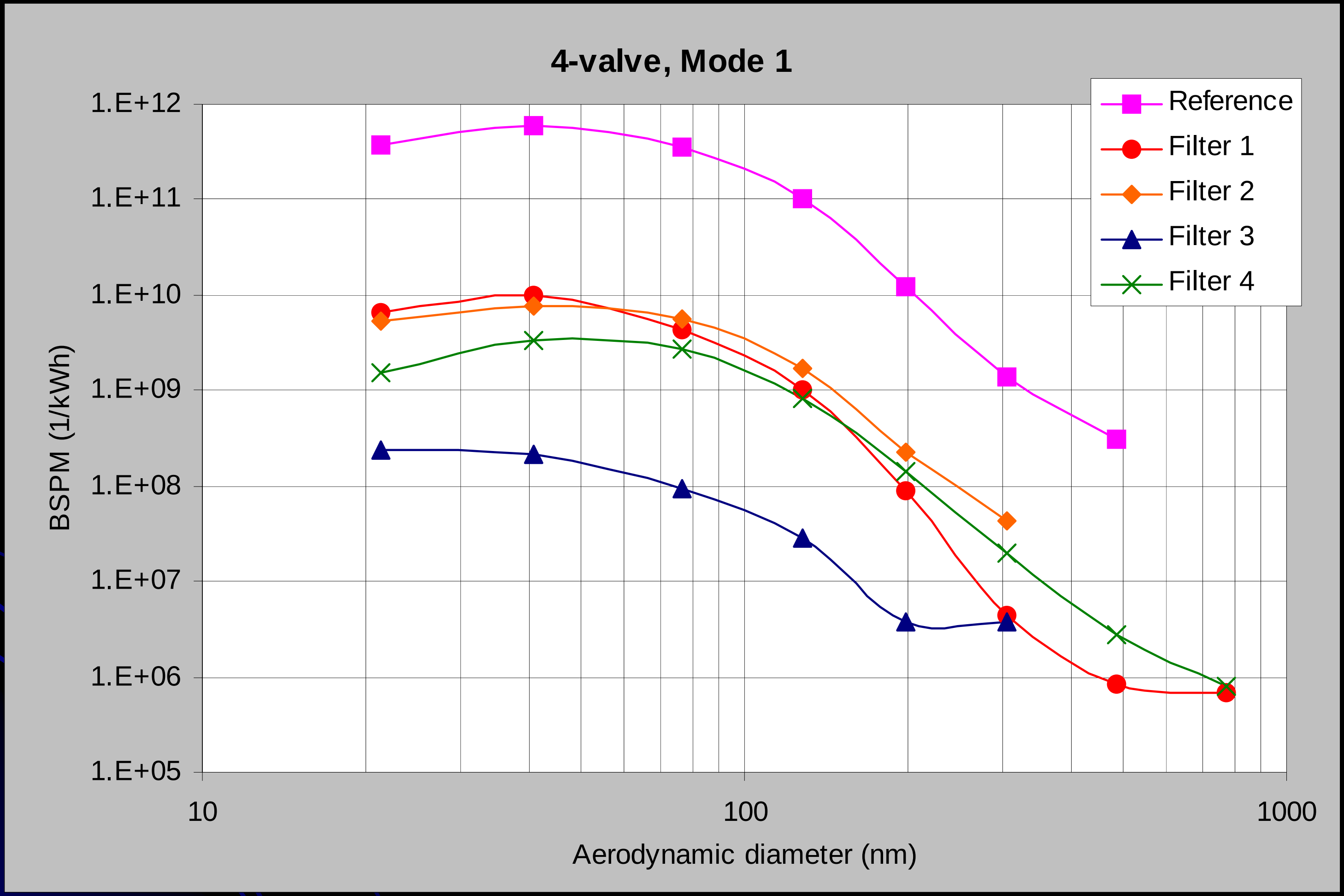

Filter performance, 5/6

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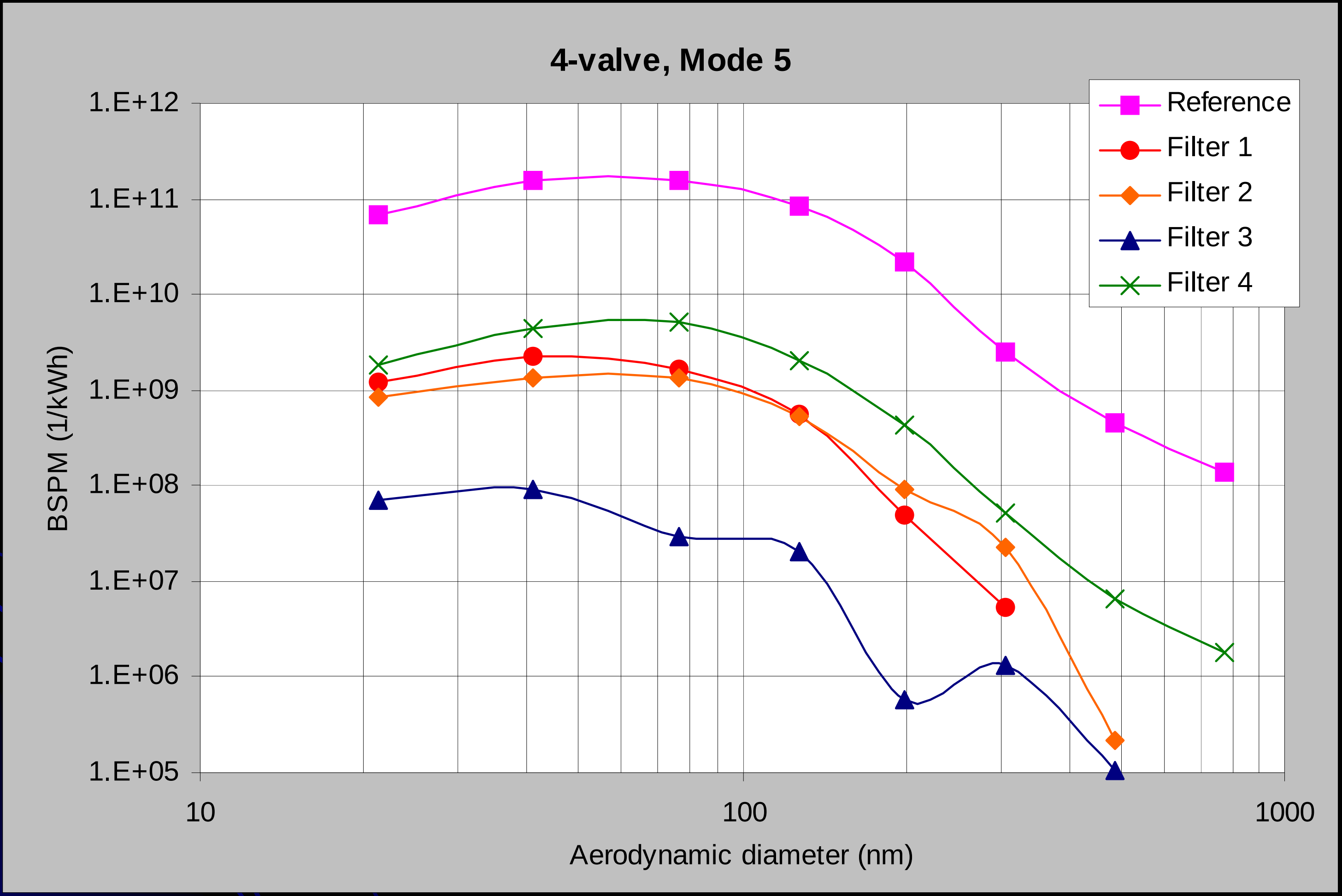

Filter performance, 6/6

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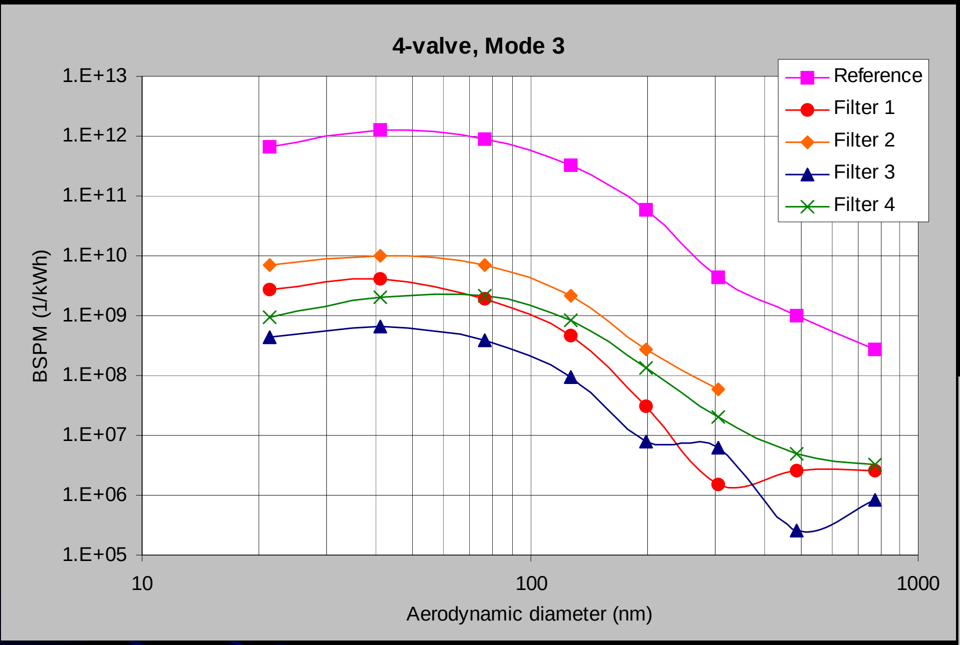

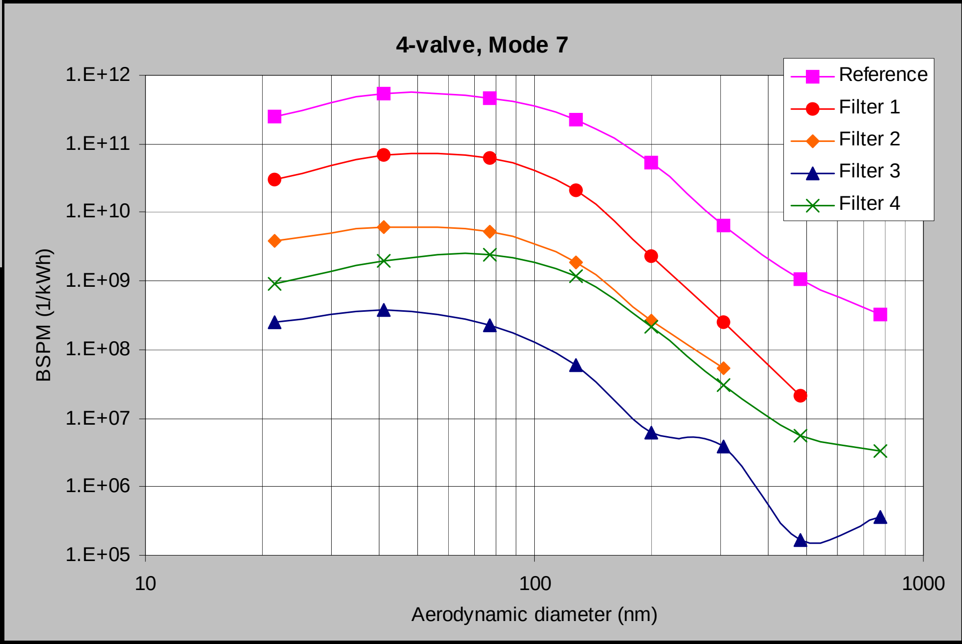

NO_2 slip, Filters, 1/2

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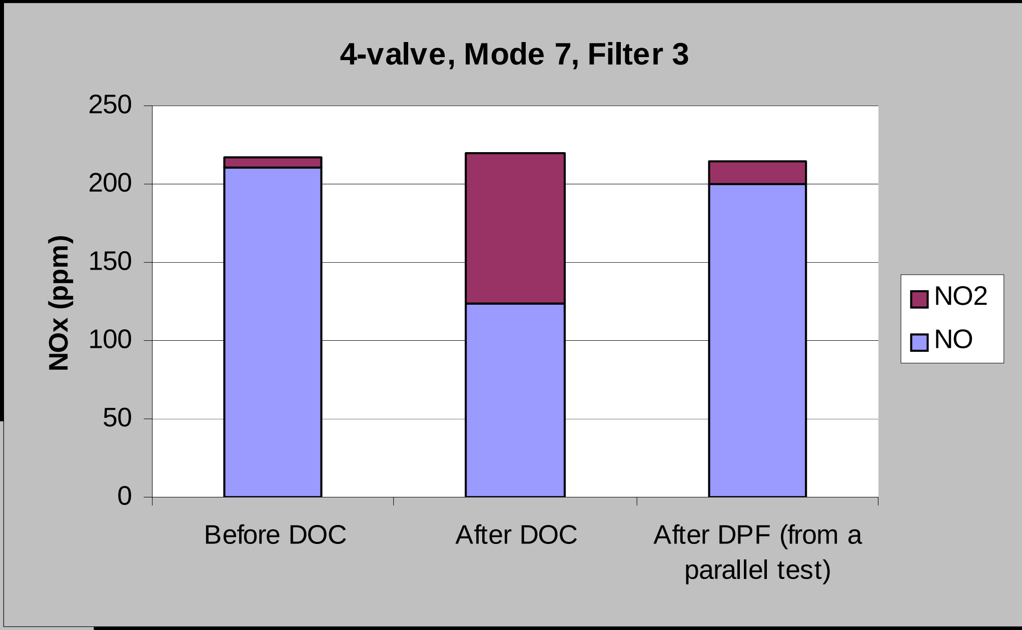

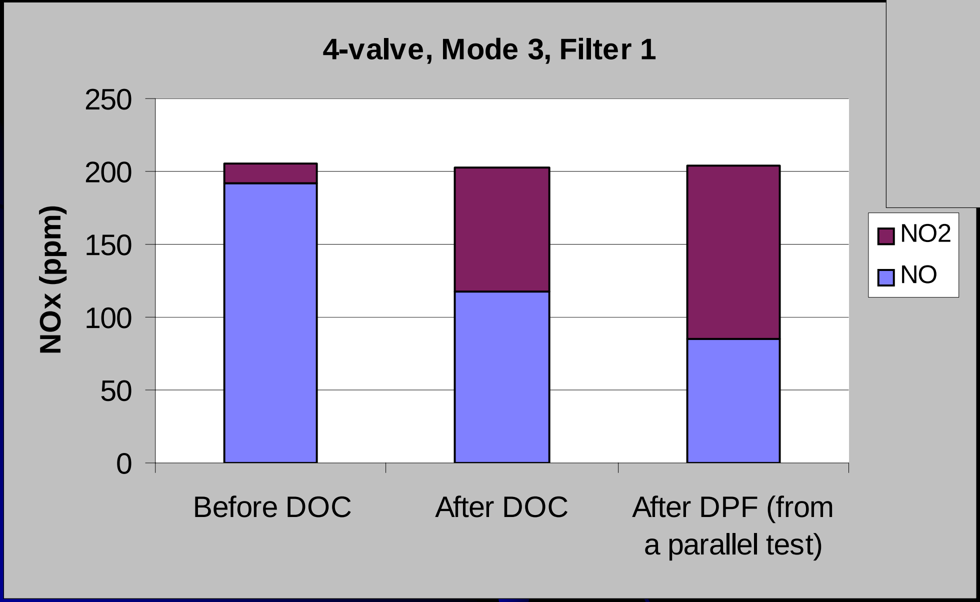

NO_2 slip, Filters, 2/2

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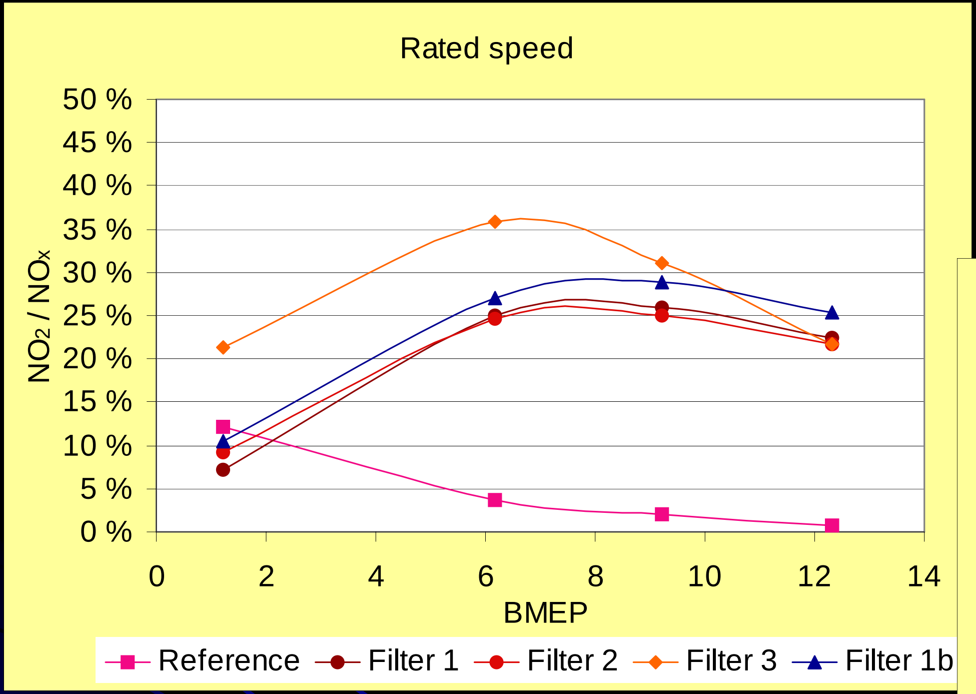

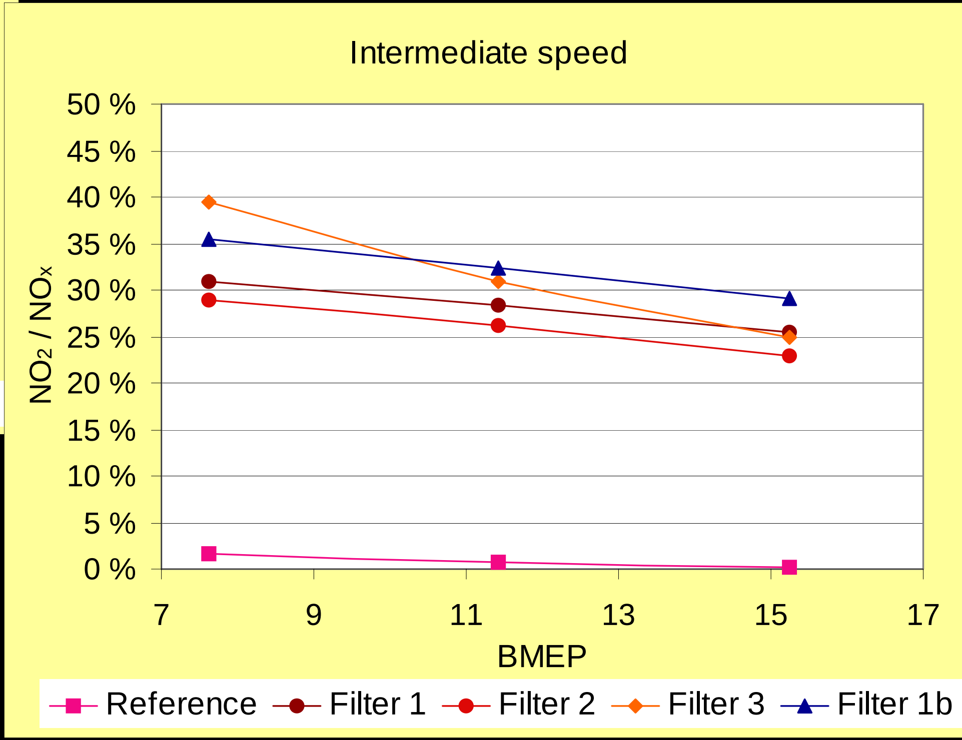

HC-SCR performance

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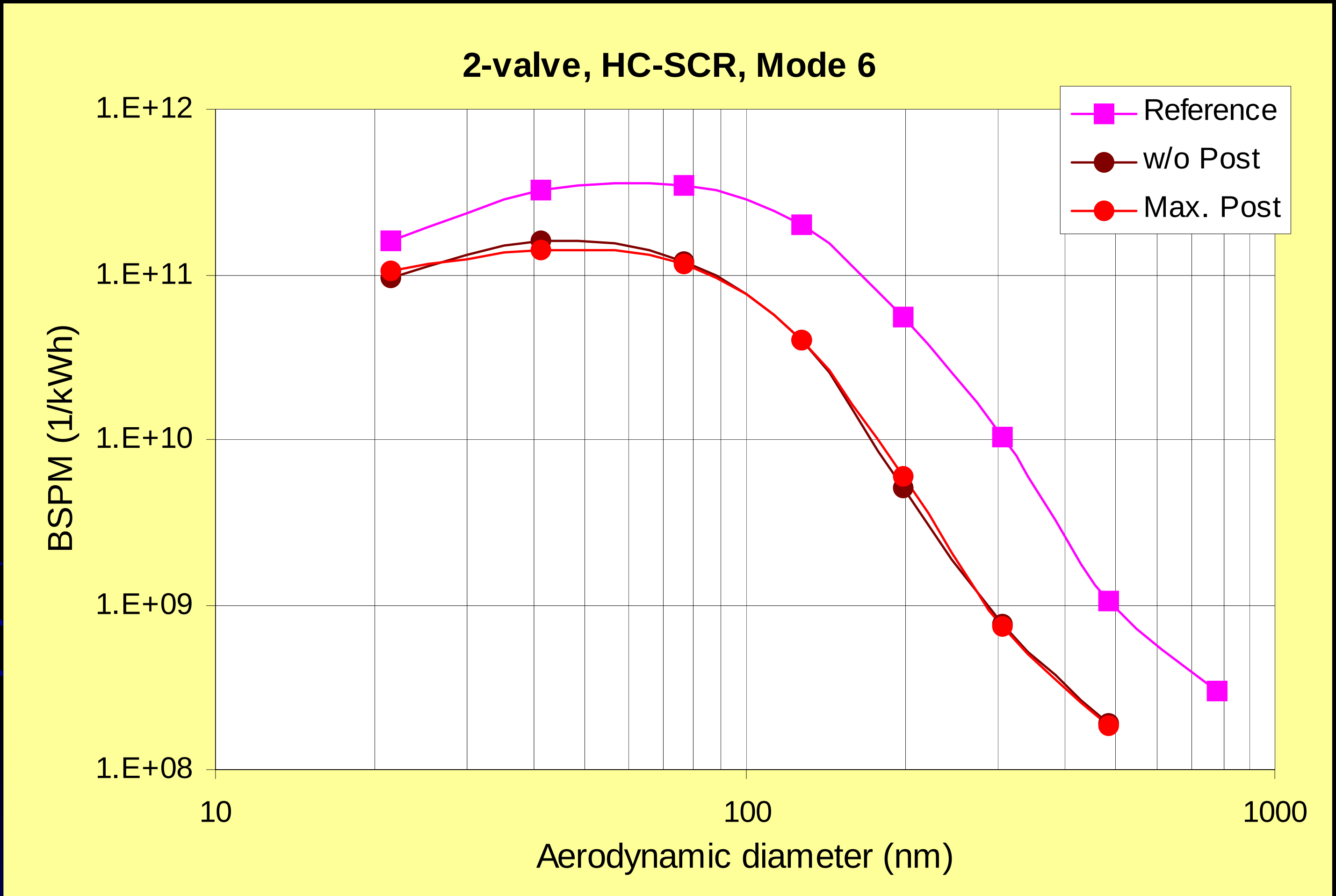

Differences between engines

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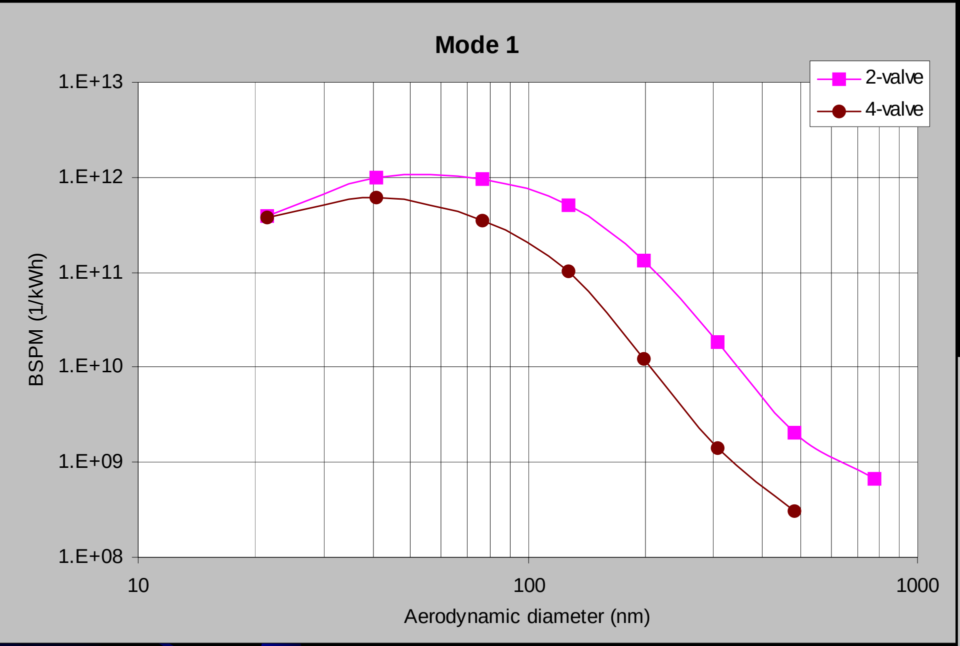

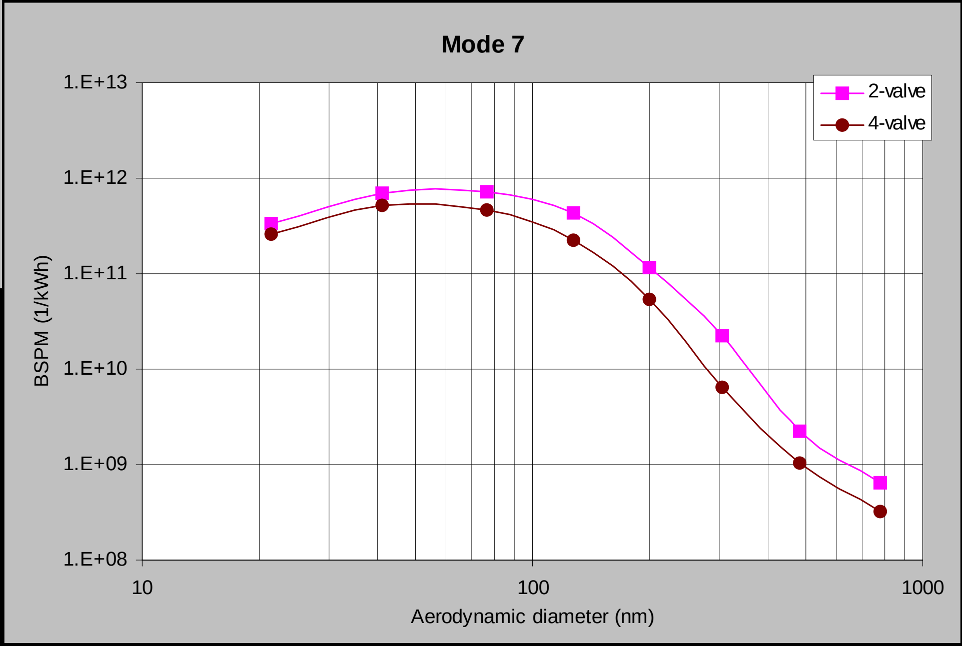

Comparative results

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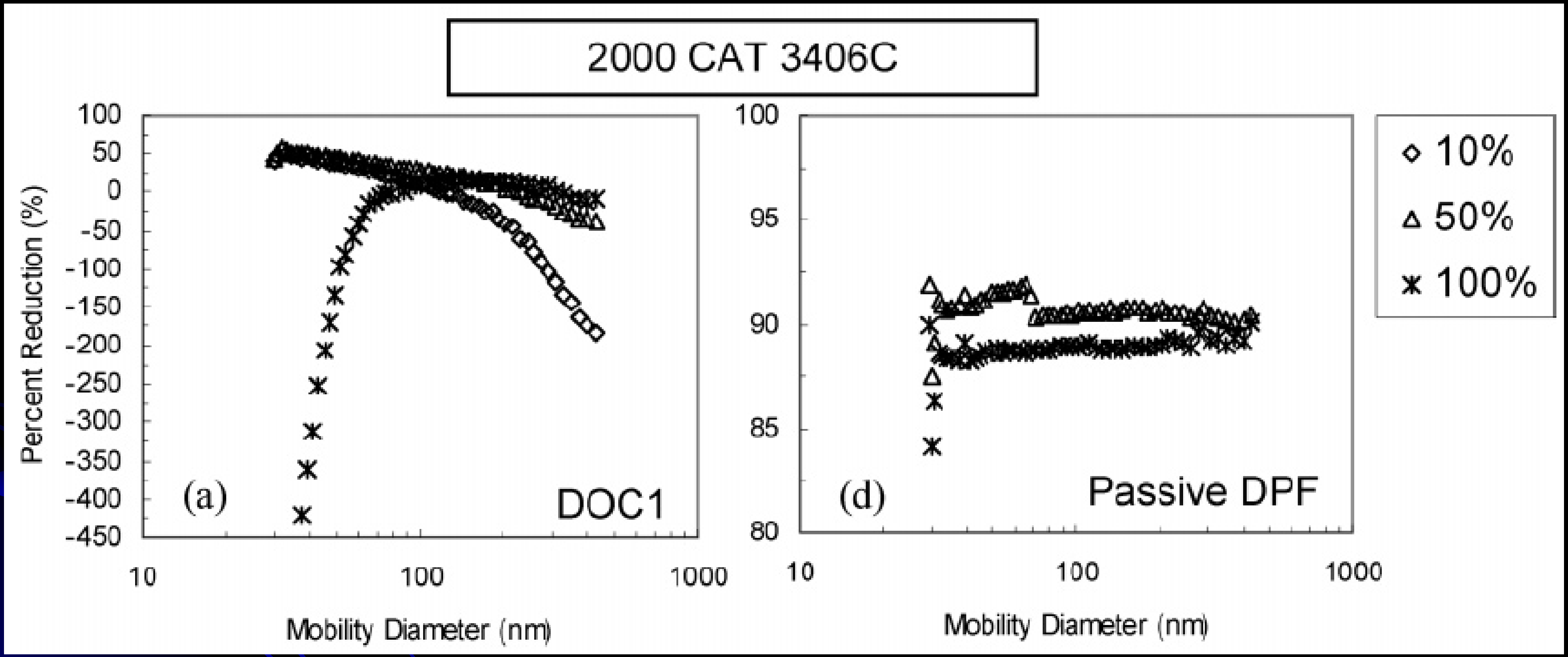

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Comparative results

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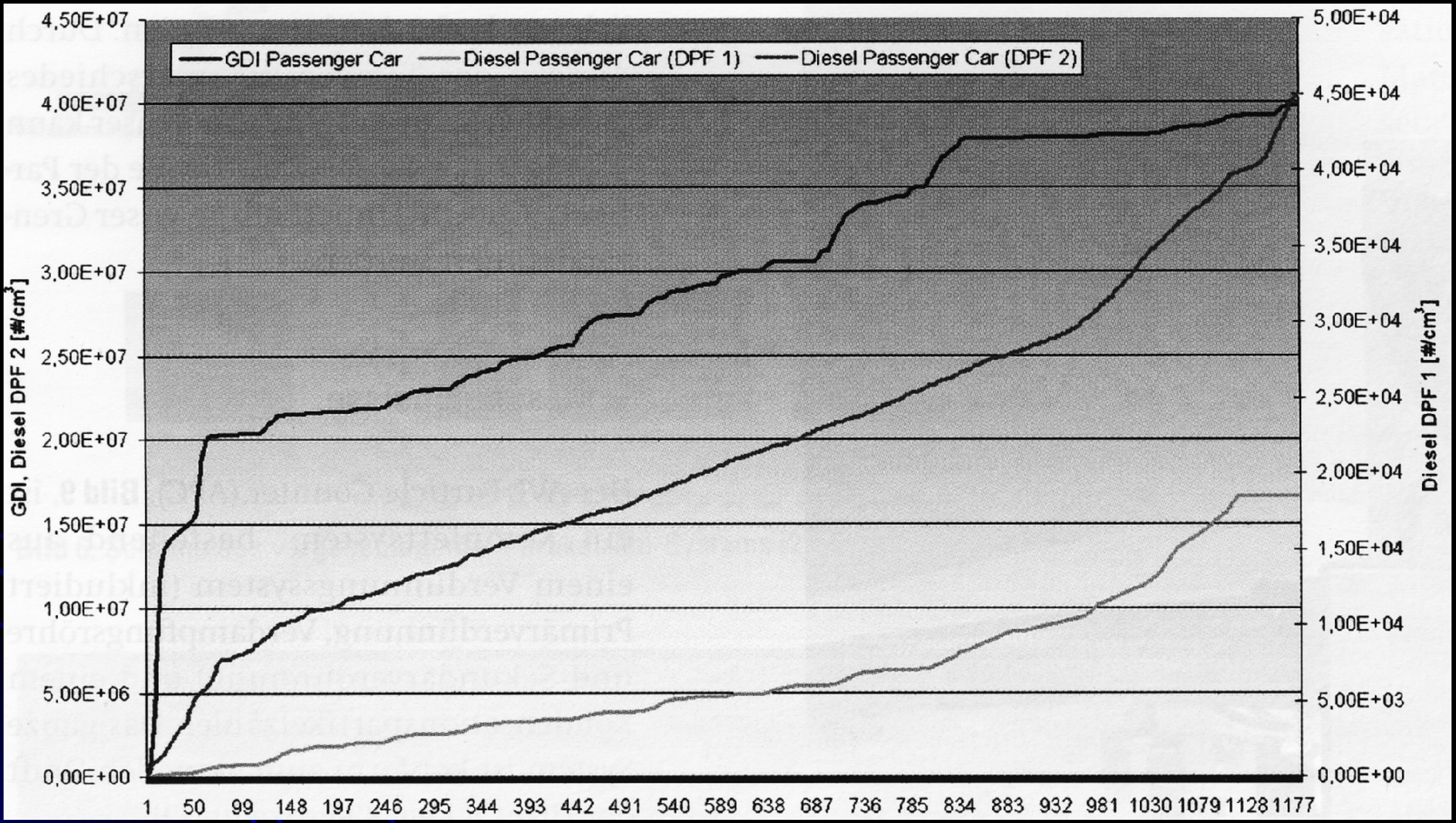

Schindler, W. et al.. (2008). Herausforderung Partikelmessung für Euro 5/6 und alternative Partikelmesstechnik. MTZ, Vol. 69, p. 502-510.

Exhaust temperatures

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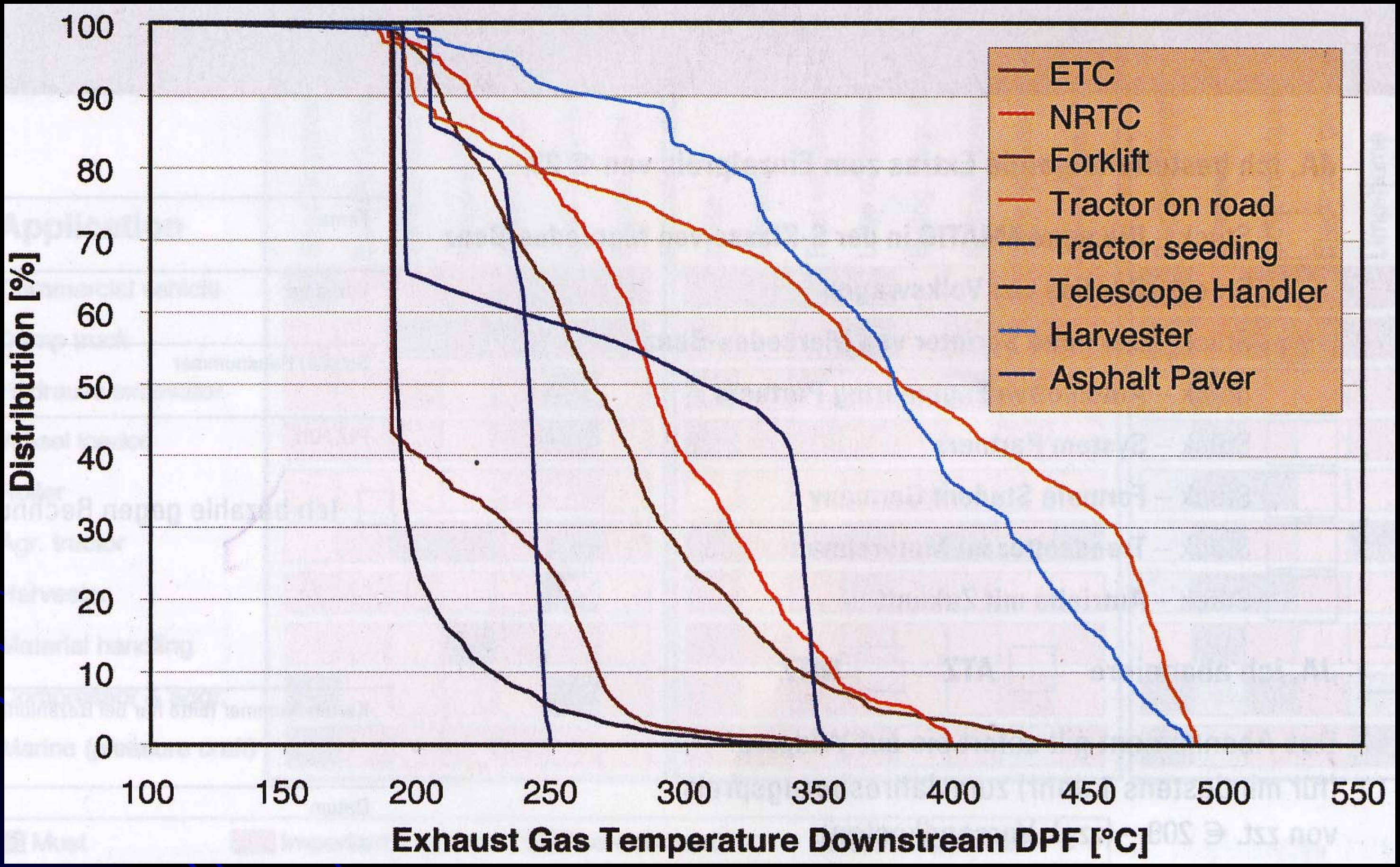

Cartus, T. et al.. (2007). Konzepte für die Emissionsgesetzgebung. MTZ, Vol. 68, p. 1054-1061.

Conclusions 1

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- There were large differences between the filters in the particle removal efficiency:
  - The best DPF reached a removal efficiency of 100% in two digits under most of the studied loading conditions
  - The efficiency of the poorest DPF ranged from 86 to 100%

Conclusions 2

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- High exhaust contents of NO_2 were measured downstream many of the studied DPFs
  - At its highest, the share of NO_2 within NO_x was
    - Almost 40% in the 2-valve engine
    - 58% in the 4-valve engine
  - Only one of the filters showed acceptable NO_2 slips

Conclusions 3

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- The HC-SCR catalyst removed larger particles fairly well:
  - Efficiencies of 82 to 90% were measured
- On the contrary, the reduction of the smallest particles remained low at 27 to 41%

Conclusions 4

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- In several practical applications, the filter temperature will remain too low for proper passive regeneration
    - Open-flow partial filters (pDPFs) will be more appropriate

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Thank you for your kind attention!