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Paper/Poster-Abstract Form

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Title: Multi-instrumental Assessment of Various Filter Media in Diesel Exhaust under Transient conditions

Abstract: (min. 300 - max 500 words)

As different Diesel Particulate Filter (DPF) designs and media are becoming widely adopted research efforts on characterization of their influence on the particle emissions intensifies. In the present work the influence of a Diesel Oxidation Catalyst (DOC) and five different Diesel Particulate Filters (DPFs) under steady and transient engine operating conditions on the particulate and gaseous emissions of a common-rail diesel engine has been studied. An array of particle measuring instrumentation (SMPS, EEPS, ELPI, CPC, DC, PAS) has been employed, all measuring at the same time from the engine exhaust. Each instrument measures a different characteristic/metric of the diesel particles (mobility size distribution, aerodynamic size distribution, total number, total surface, active surface,…) and their combination assists in building a complete characterization of the particle emissions at the various measurement locations: engine out, DOC out and DPf out. The results provide useful guidelines for selection of various filter media and measuring methodologies. In the presentation among other themes to be discussed are the inter-comparison of SMPS and EEPS measurements which are found to exhibit small but systematic differences, the evolution of the collection efficiency of each filter medium (evaluated with respect to each of the characteristic metrics measured by each instrument) under steady state and transient conditions as a function of soot load of the filter and the particle emissions during filter regeneration.

Short CV:

Dr. Athanasios G. Konstandopoulos, is the founder and director of the *Aerosol & Particle Technology (APT) Laboratory*. He is a specialist in combustion aerosols and nanoparticles, with extensive research and engineering consulting experience. He is the author of numerous scientific and technical papers and an SAE Fellow. He has a hybrid background in Mechanical (*Dipl. ME, Aristotle University of Thessaloniki, 1985; MSc ME Michigan Tech, 1987) and Chemical Engineering (MSc, MPhil, PhD, Yale University, 1991*).

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Multi-instrumental Assessment of Various Filter Media in Diesel Exhaust under Transient Conditions

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Outline

- Steady state tests: instrument comparison
- Transient tests:
  - instrument comparison
  - assessment of transient filtration efficiency as function of soot load
- Concluding Remarks

PARTICLE MEASUREMENT SYSTEMS EMPLOYED

- **SMPS (TSI Long DMA and Ultrafine CPC model No. 3025)**
- **Standalone CPC (TSI Model No. 3022)**
- **EEPS**

  All 3 measuring from an in-house 3-stage heated diluter

- **ELPI**

  Measuring from a DEKATI 2-stage heated diluter

- **NANOMET (PAS & DC)**

  Measuring from a MATTER ENG. rotary heated diluter

Test matrix

Common rail, 1.9 L Diesel Engine, rated at 80 HP

Steady state points

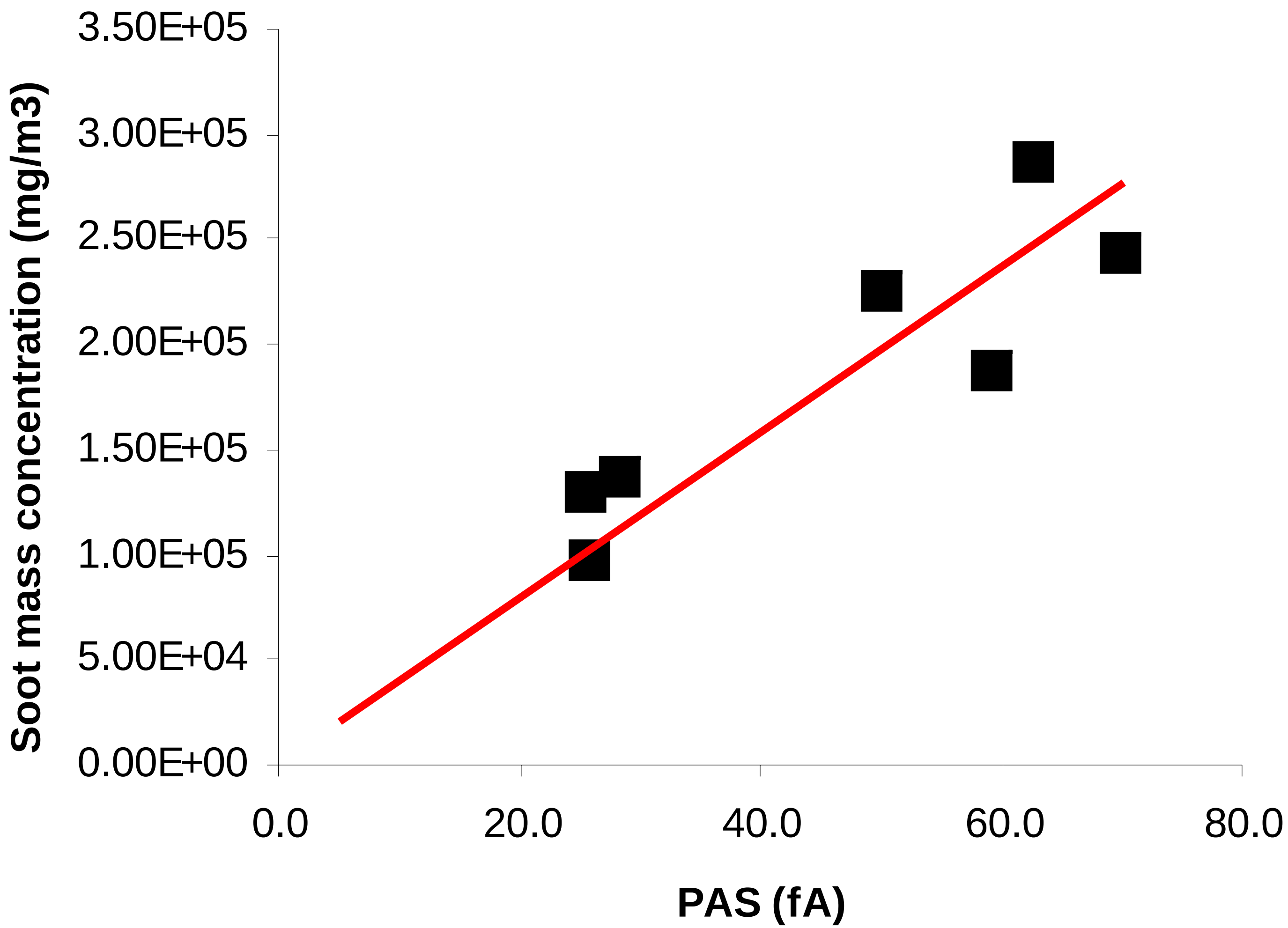
Engine point	Speed, rpm	BMEP, bar	Soot mass concentration, mg/m^3	Exhaust mass flow, kg/h	Exhaust temperature , C
1	1500	3	50.2	75	259
2	1500	4	70.0	77	292
3	1500	5	59.3	86	327
4	2350	3.8	25.4	126	307
5	2250	6.7	25.9	157	381
6	2450	8.8	35.0	207	448
7	2500	5	28.4	153	348
8	1700	5.5	62.8	104	351

Transient cycle NEDC

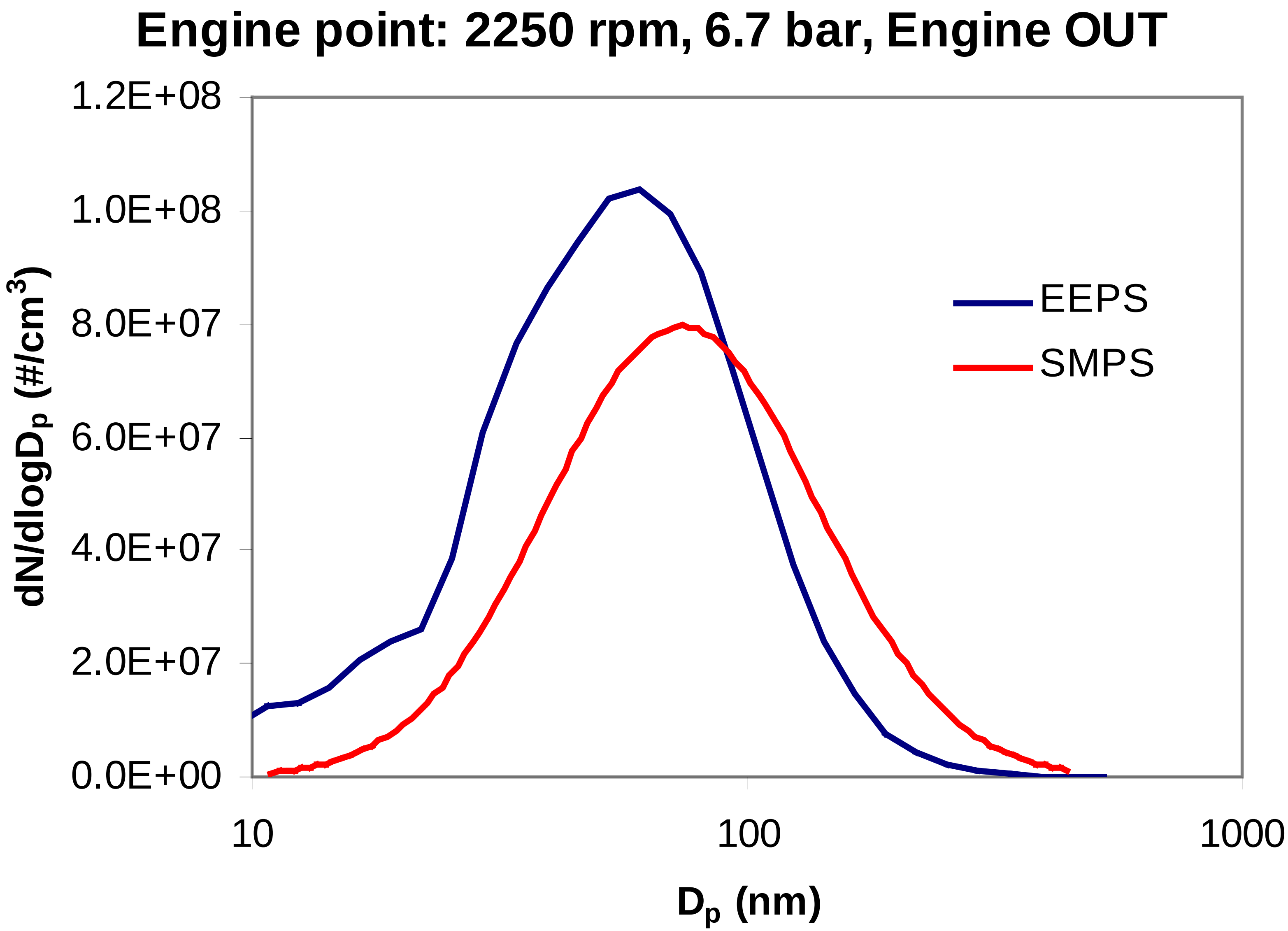
DPFs studied

DPF	Type / Material	Dimensions (in)	Filtration area (m^2)	Porosity (%)
1	Non-oxide ceramic wall-flow monolith	5.66x6	1.90	42
2	High porosity oxide ceramic wall-flow monolith	5.66x6	2.00	60
3	Standard porosity wall-flow monolith	5.66x6	1.13	48
4	Coarse grain non-oxide ceramic wall-flow monolith	5.66x8.4	1.70	42
5	Fibrous fillter	5 x 3	0.08	85

Engine out – Soot concentration vs. PAS

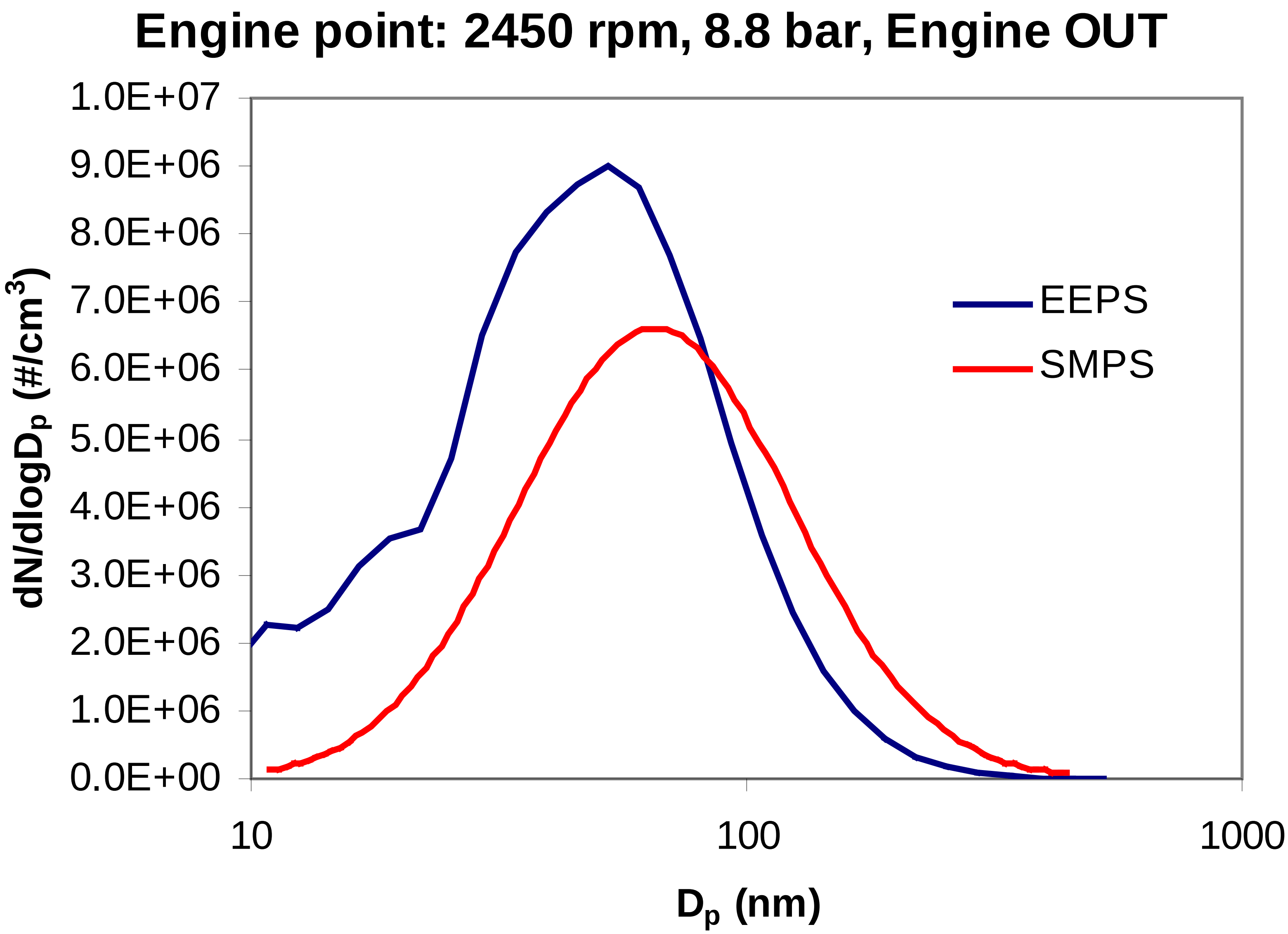


Engine out



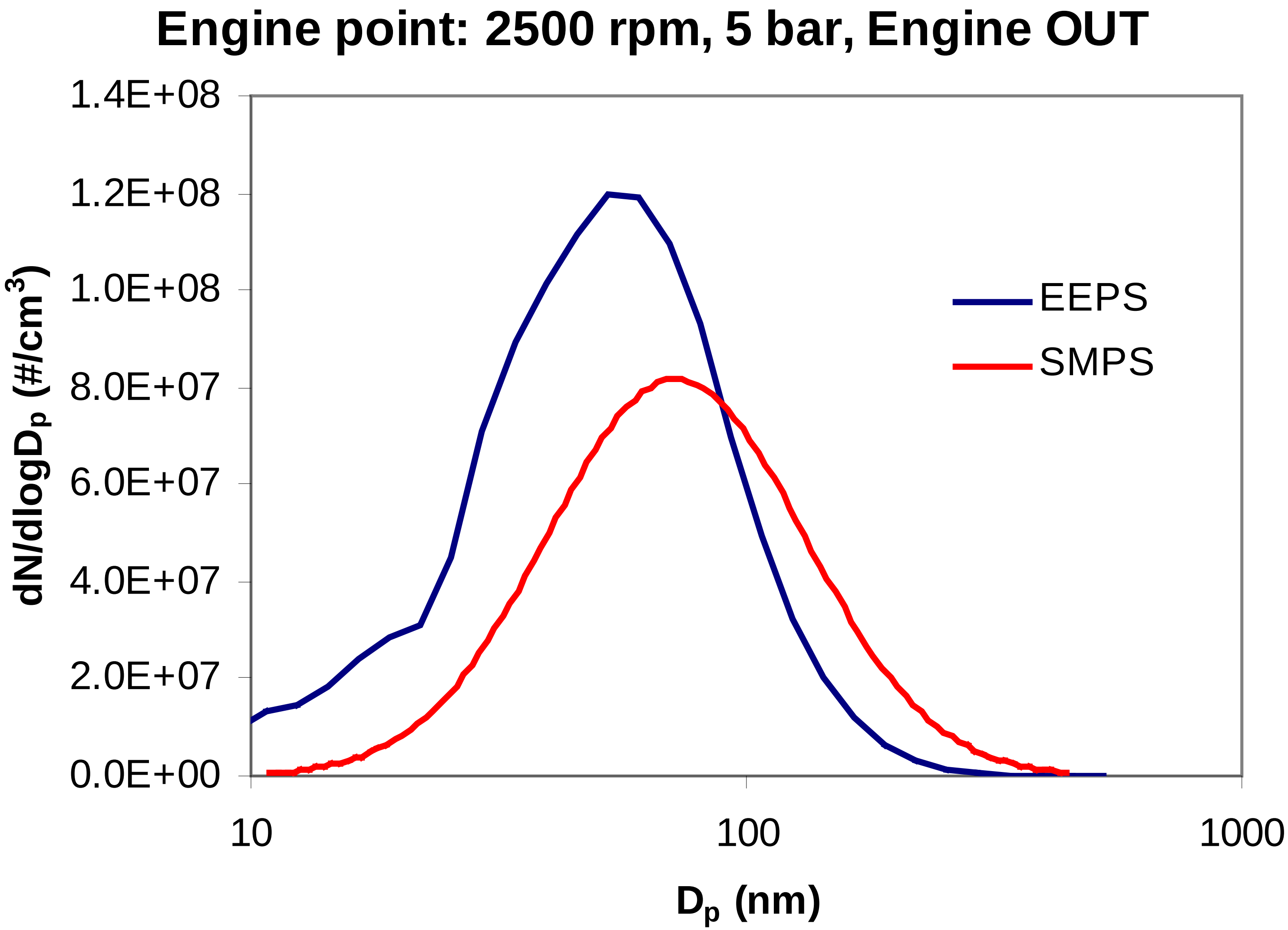
Engine point: 2250 rpm, 6.7 bar, Engine OUT
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
dN/dlogDp (#/cm3)
10
100
1000
Dp (nm)
EEPS
SMPS

Engine out



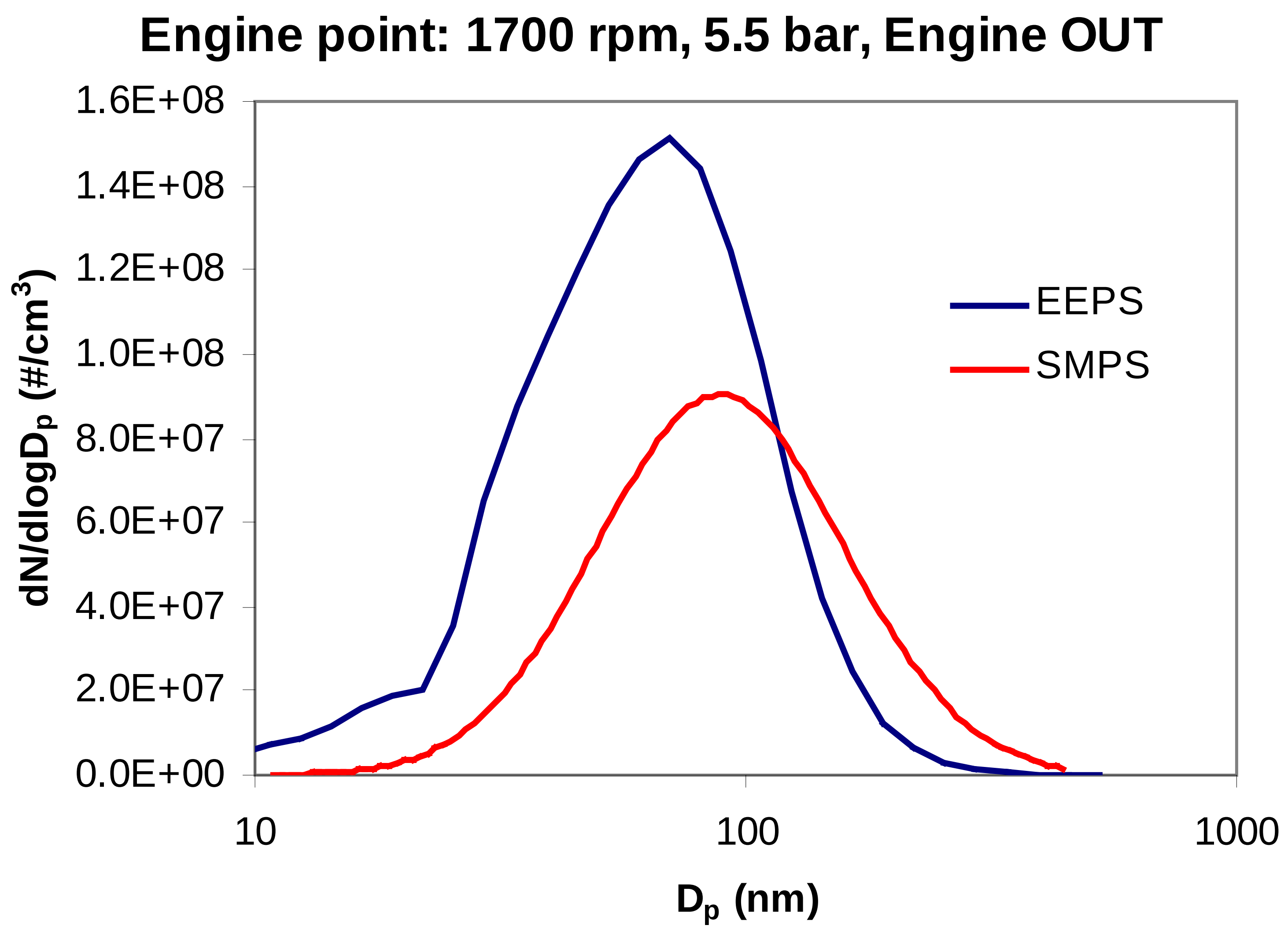
Engine point: 2450 rpm, 8.8 bar, Engine OUT
1.0E+07
9.0E+06
8.0E+06
7.0E+06
6.0E+06
5.0E+06
4.0E+06
3.0E+06
2.0E+06
1.0E+06
0.0E+00
dN/dlogDp (#/cm3)
EEPS
SMPS
10
100
1000
Dp (nm)

Engine out



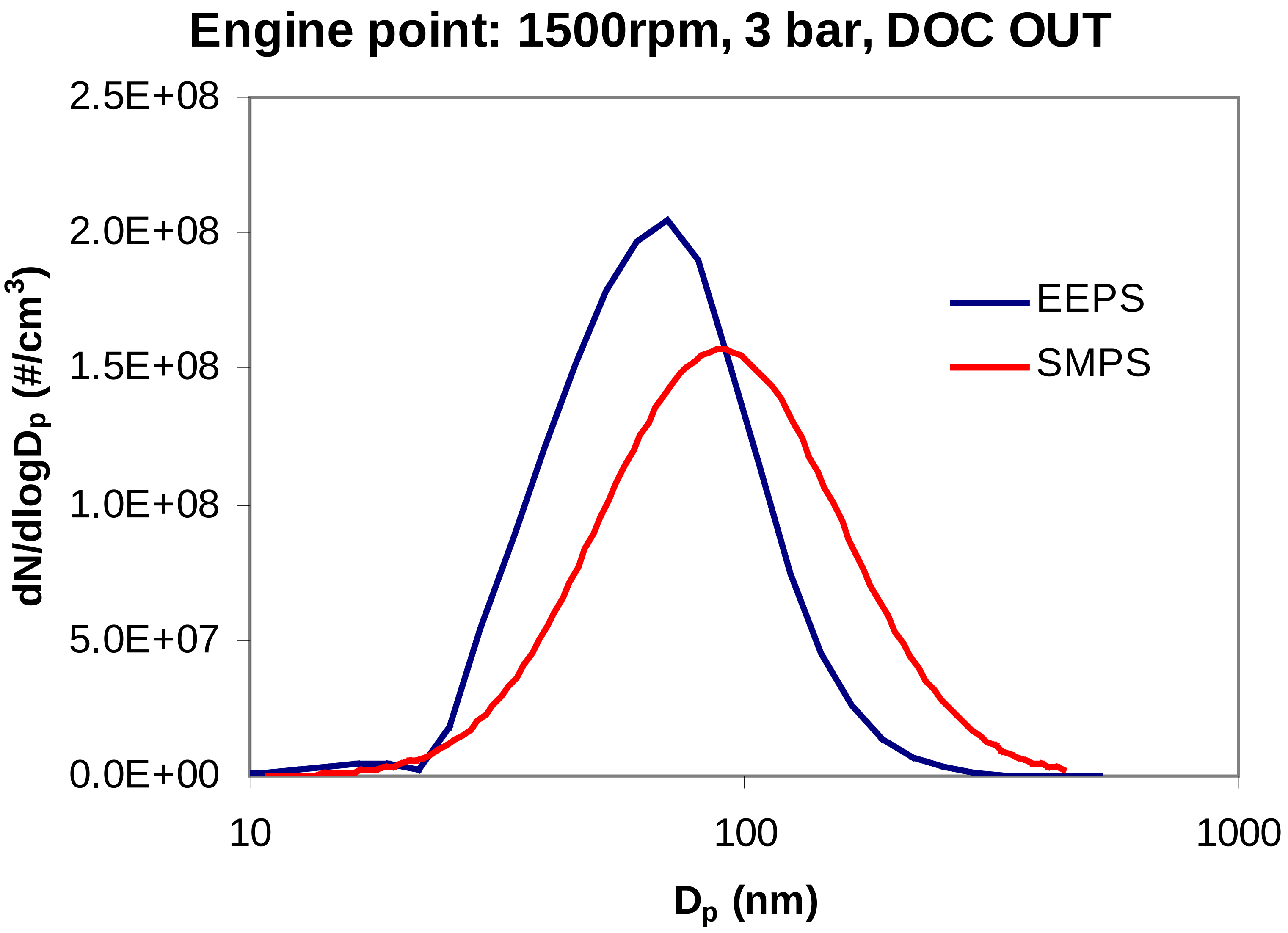
Engine point: 2500 rpm, 5 bar, Engine OUT
1.4E+08
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
dN/dlogDp (#/cm3)
10
100
1000
Dp (nm)
EEPS
SMPS

Engine out

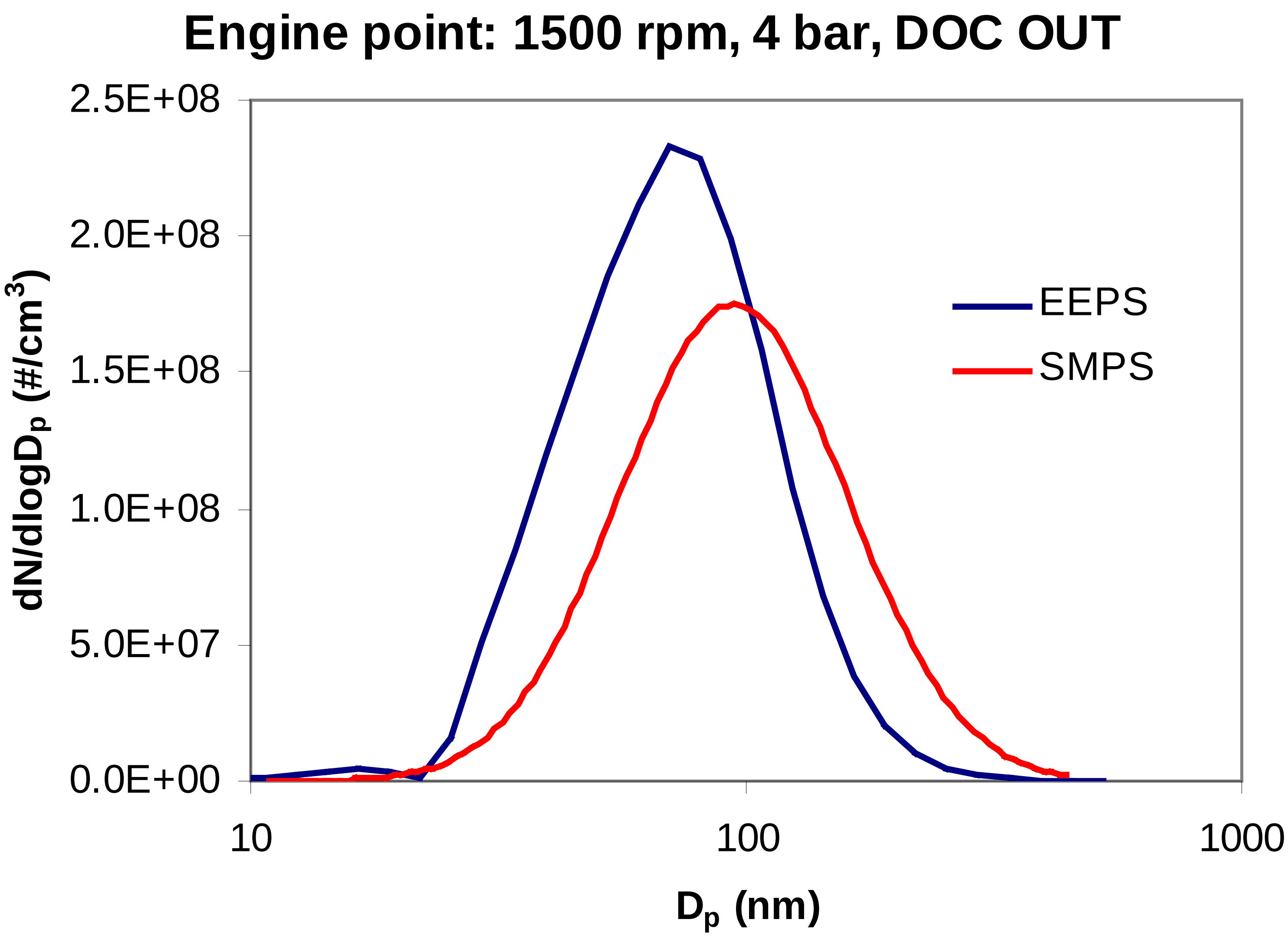


Engine point: 1700 rpm, 5.5 bar, Engine OUT
1.6E+08
1.4E+08
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
dN/dlogDp (#/cm3)
10
100
1000
Dp (nm)
EEPS
SMPS

DOC out

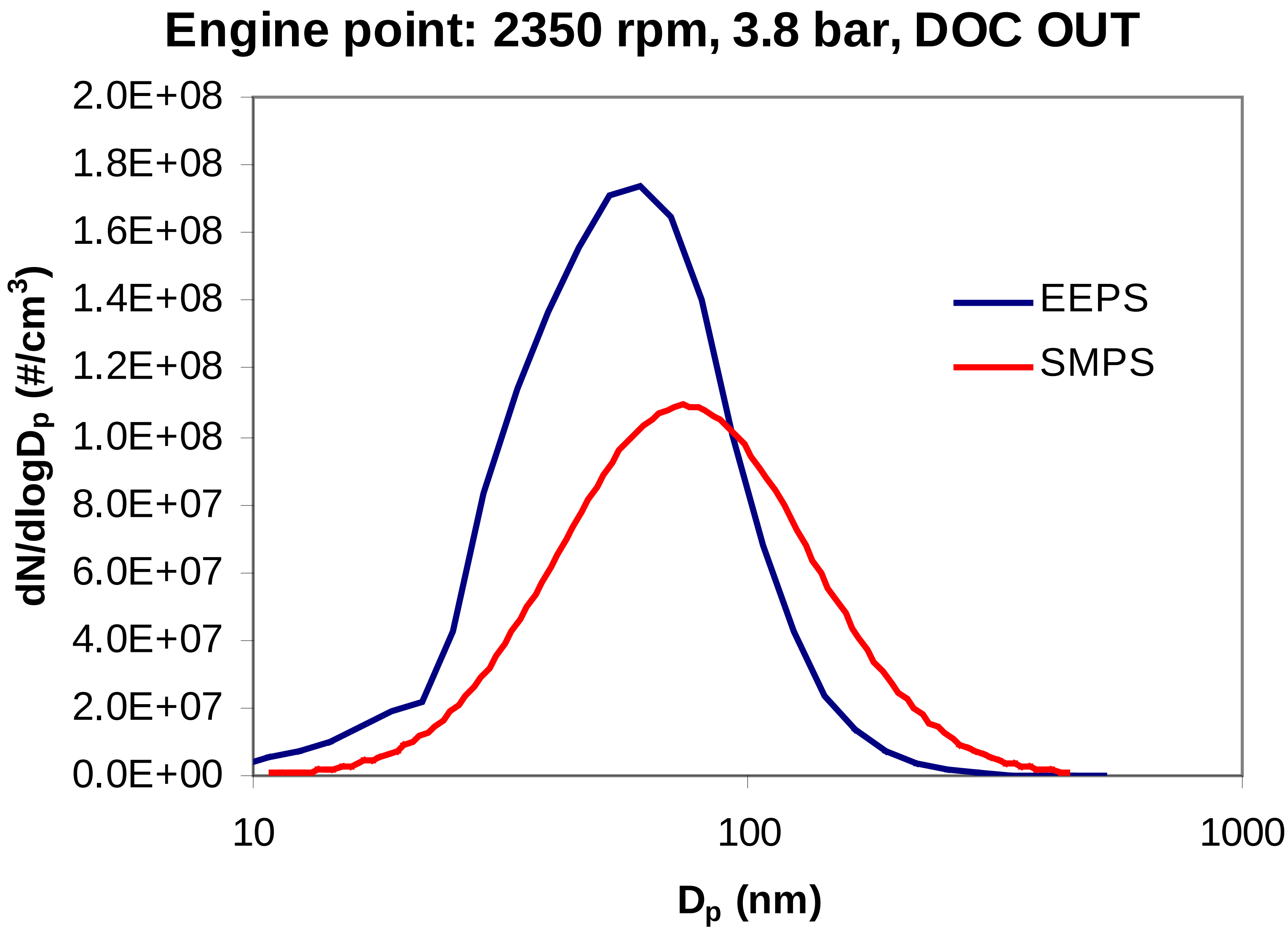

Engine point: 1500rpm, 3 bar, DOC OUT
2.5E+08
2.0E+08
1.5E+08
1.0E+08
5.0E+07
0.0E+00
dN/dlogDp (#/cm3)
10
100
1000
Dp (nm)
EEPS
SMPS

DOC out

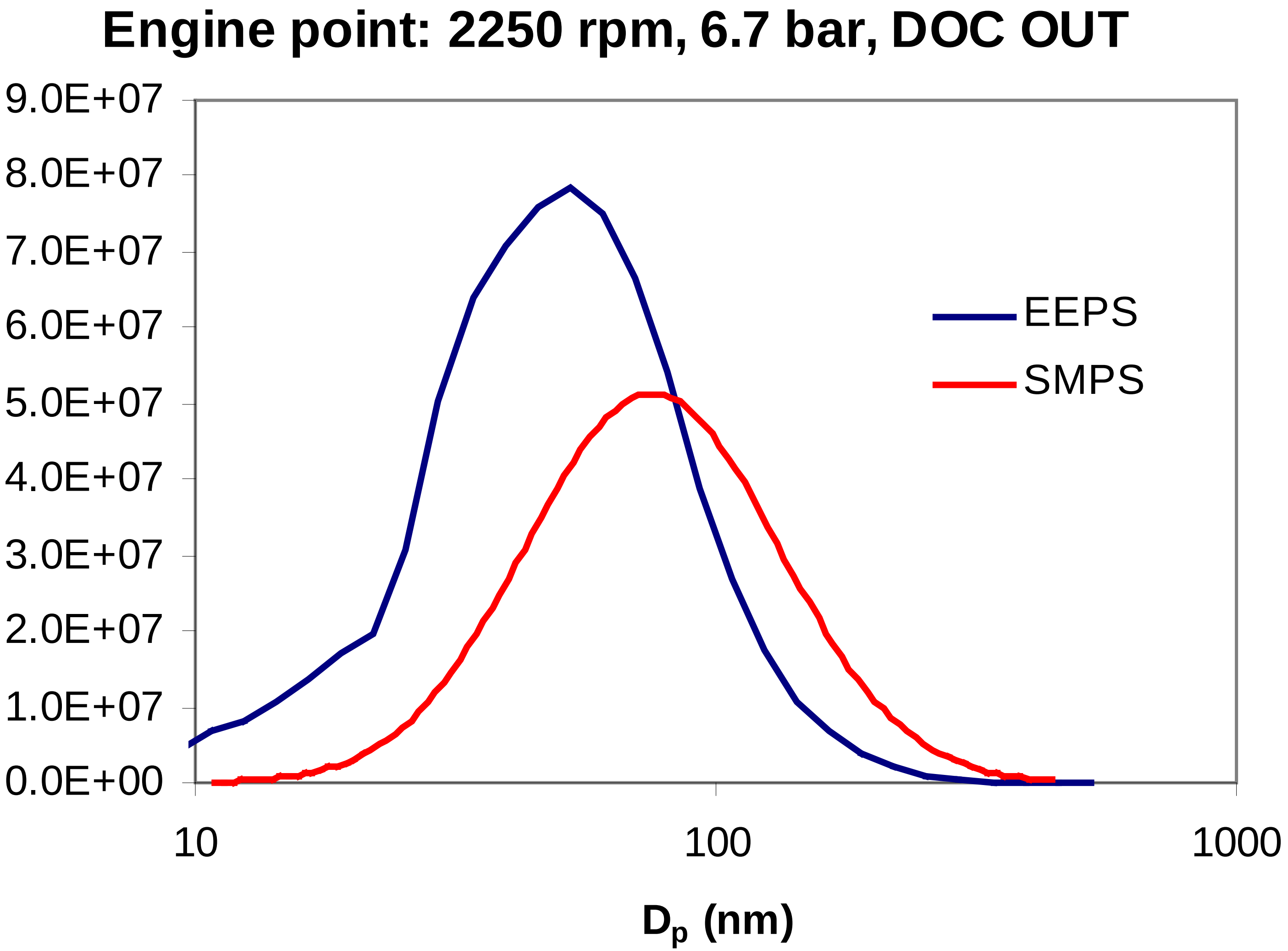


Engine point: 1500 rpm, 4 bar, DOC OUT
2.5E+08
2.0E+08
1.5E+08
1.0E+08
5.0E+07
0.0E+00
dN/dlogDp (#/cm3)
10
100
1000
Dp (nm)
EEPS
SMPS

DOC out

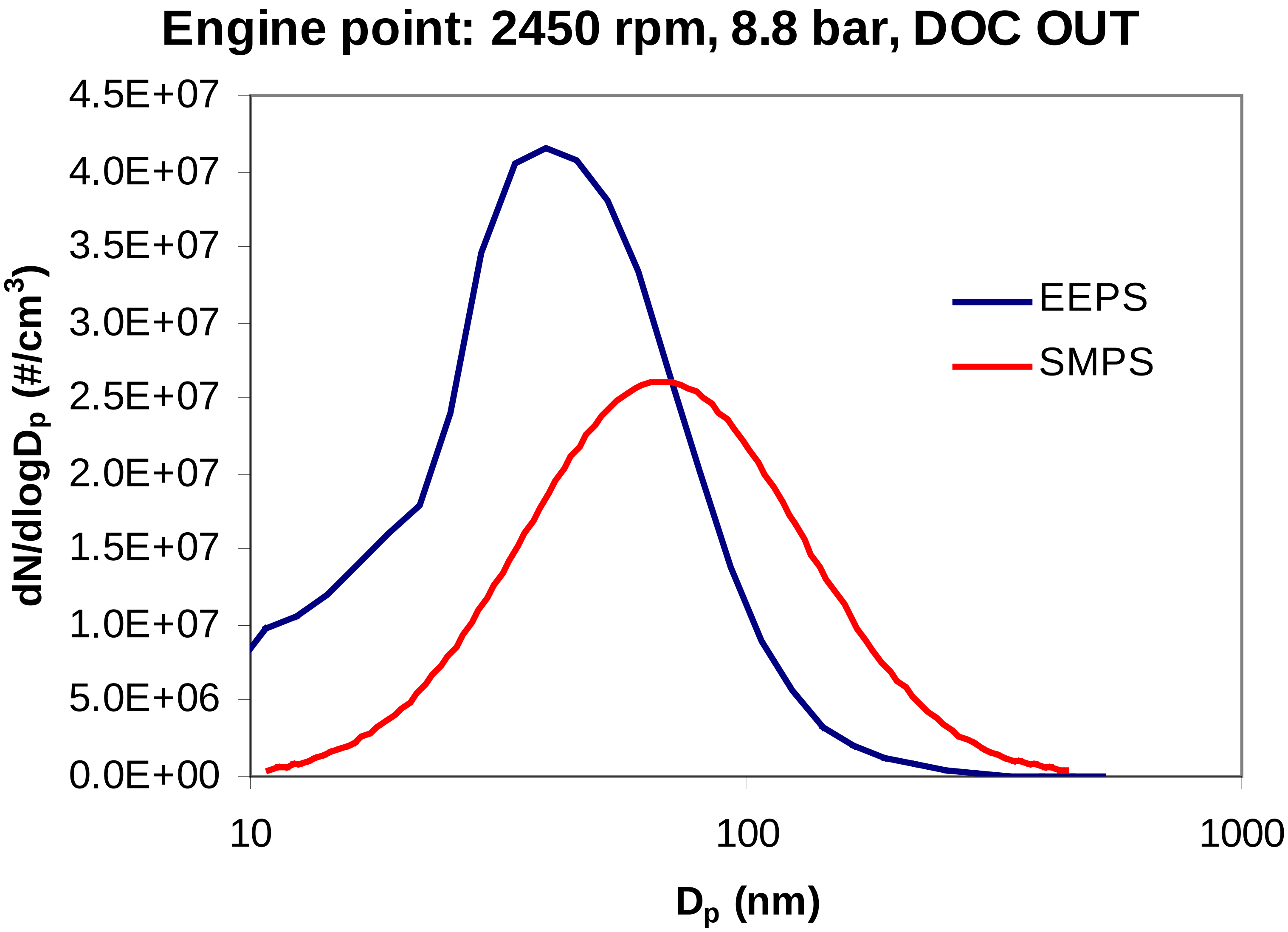

Engine point: 2350 rpm, 3.8 bar, DOC OUT
2.0E+08
1.8E+08
1.6E+08
1.4E+08
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
dN/dlogDp (#/cm3)
10
100
1000
Dp (nm)
EEPS
SMPS

DOC out



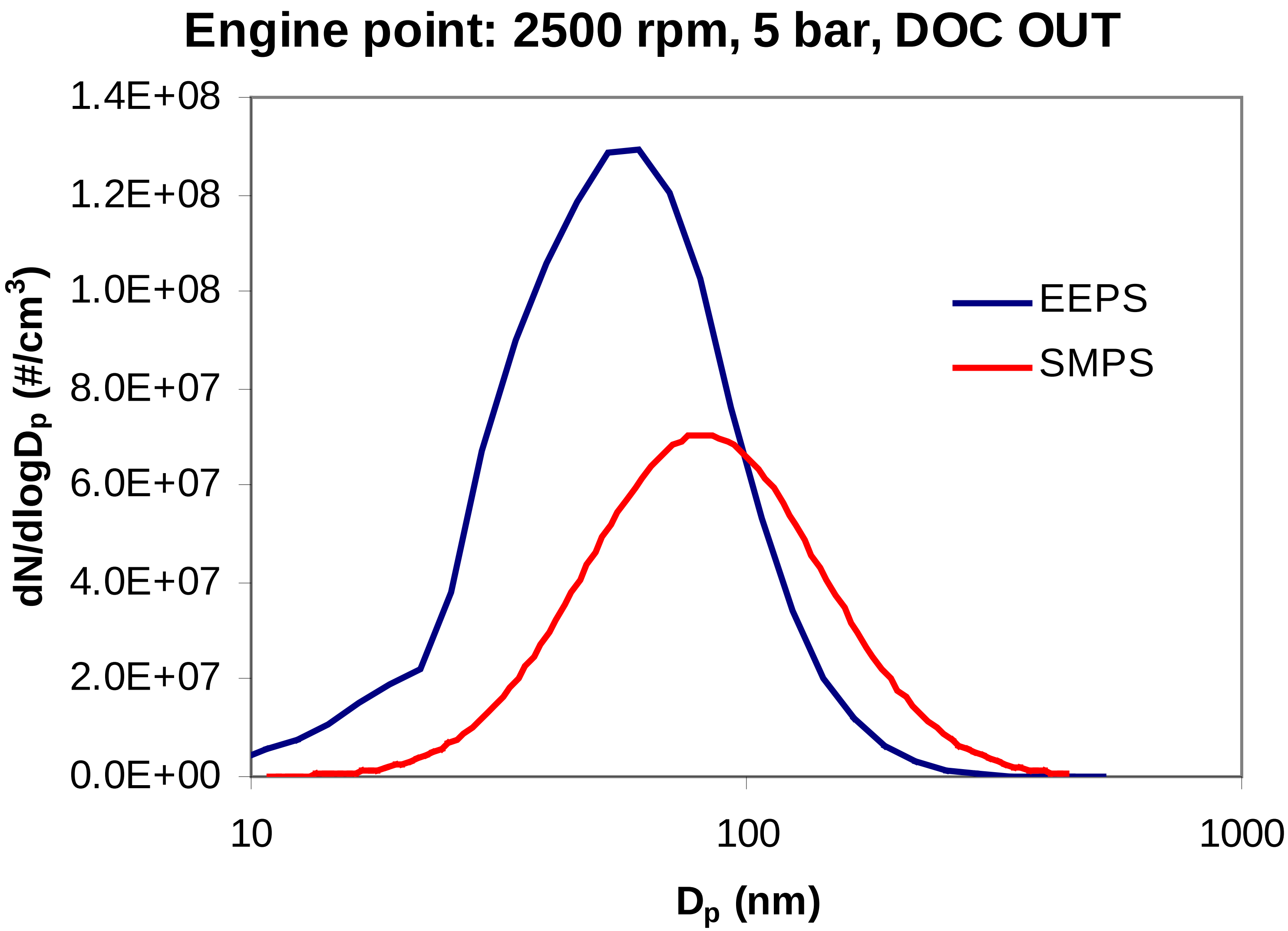
Engine point: 2250 rpm, 6.7 bar, DOC OUT
9.0E+07
8.0E+07
7.0E+07
6.0E+07
5.0E+07
4.0E+07
3.0E+07
2.0E+07
1.0E+07
0.0E+00
10
100
1000
Dp (nm)
EEPS
SMPS

DOC out

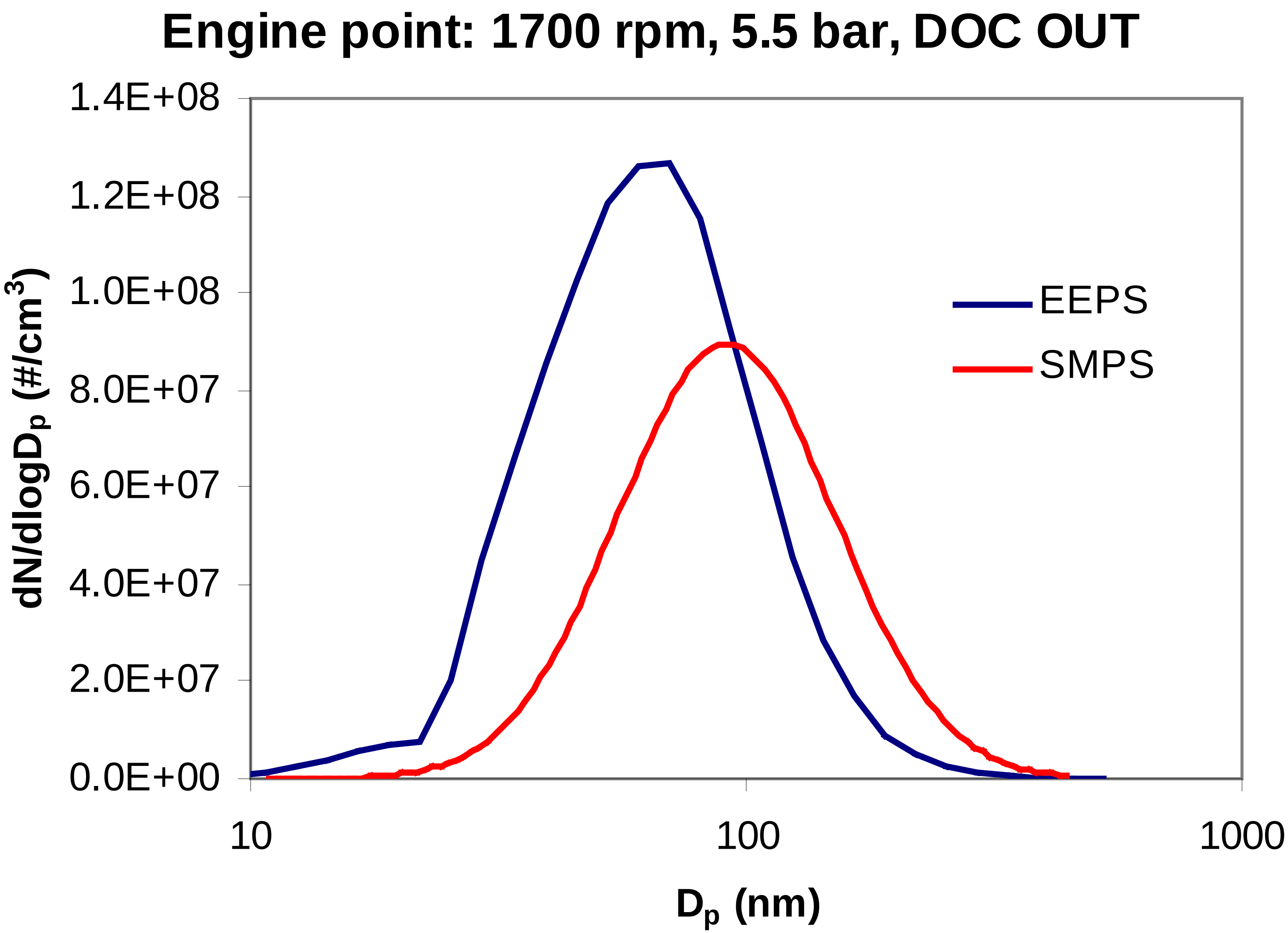


Engine point: 2450 rpm, 8.8 bar, DOC OUT
4.5E+07
4.0E+07
3.5E+07
3.0E+07
2.5E+07
2.0E+07
1.5E+07
1.0E+07
5.0E+06
0.0E+00
dN/dlogDp (#/cm3)
10
100
1000
Dp (nm)
EEPS
SMPS

DOC out

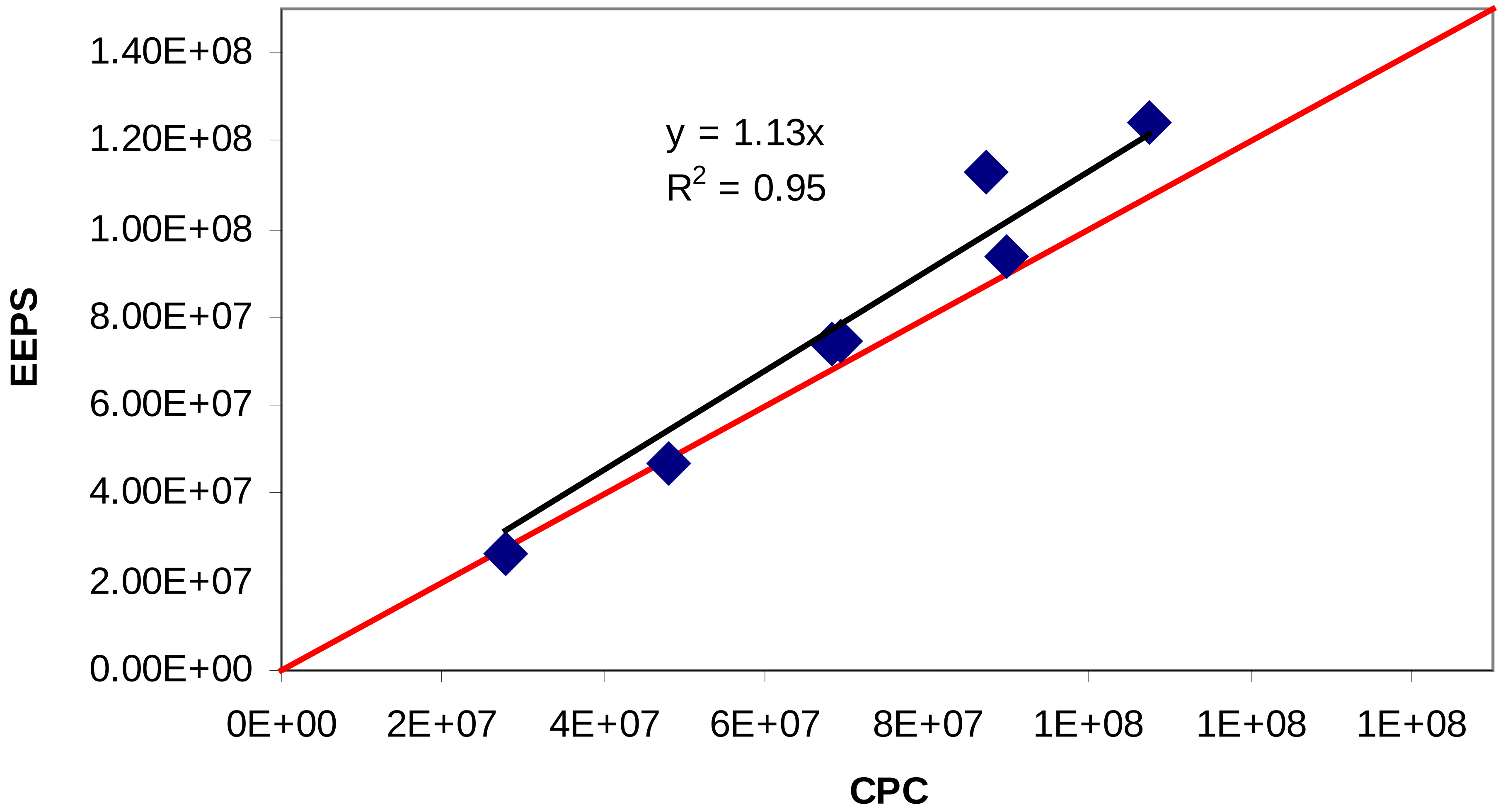

Engine point: 2500 rpm, 5 bar, DOC OUT
1.4E+08
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
10
100
1000
dN/dlogDp (#/cm3)
Dp (nm)
EEPS
SMPS

DOC out

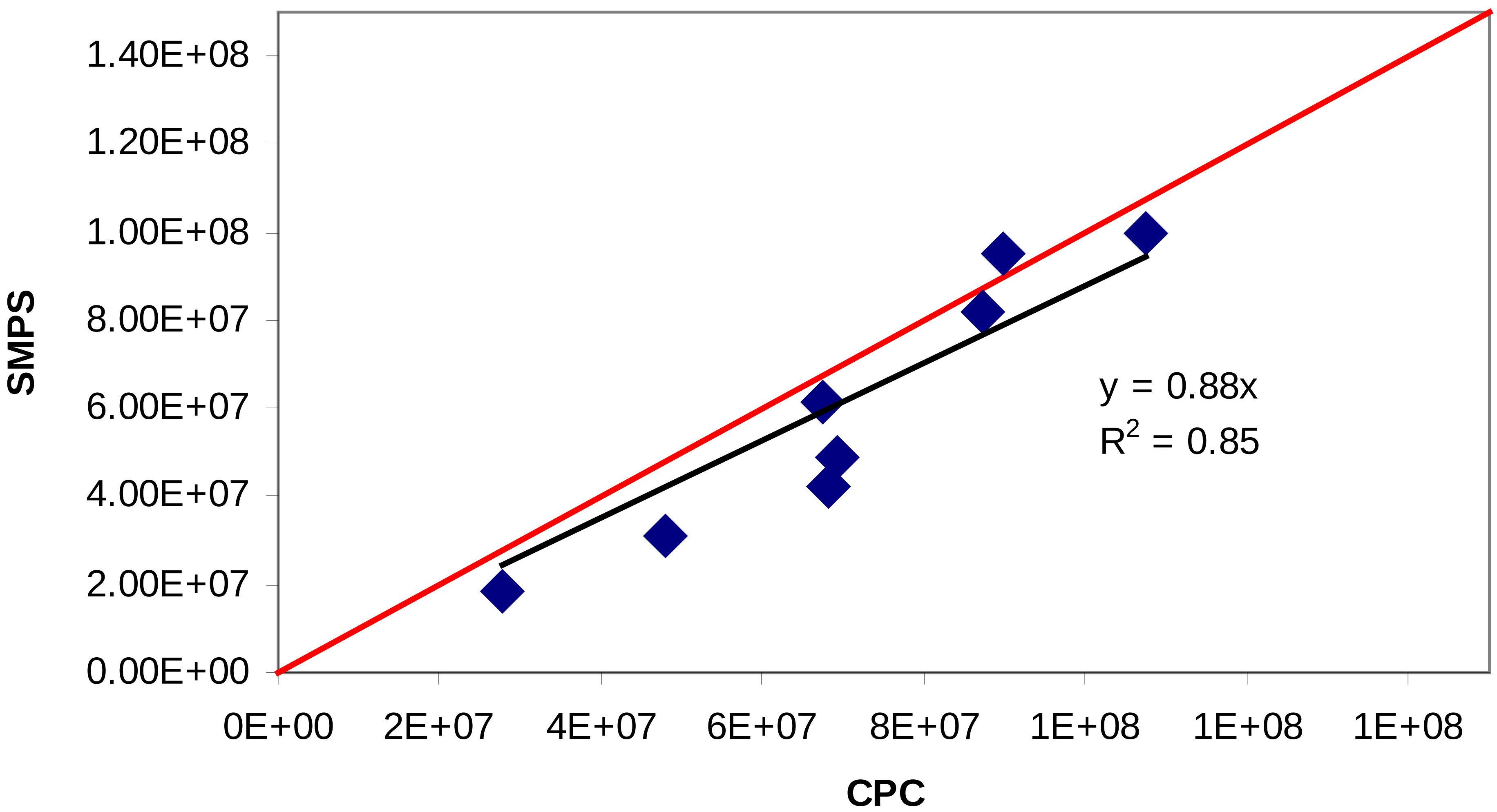


Engine point: 1700 rpm, 5.5 bar, DOC OUT
1.4E+08
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
dN/dlogDp (#/cm3)
10
100
1000
Dp (nm)
EEPS
SMPS

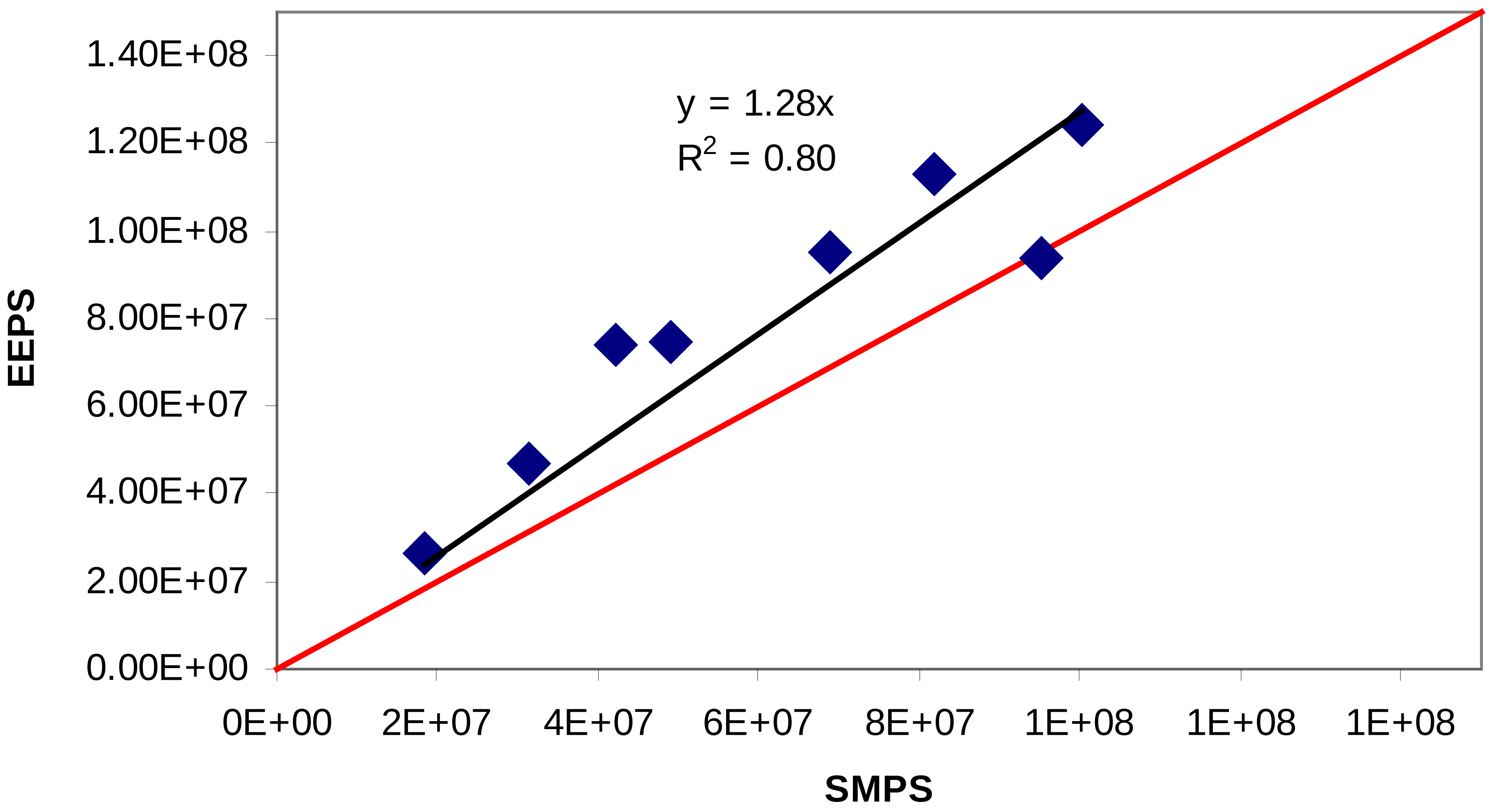
DOC out – Total Concentration (# / cm³) – EEPS vs CPC



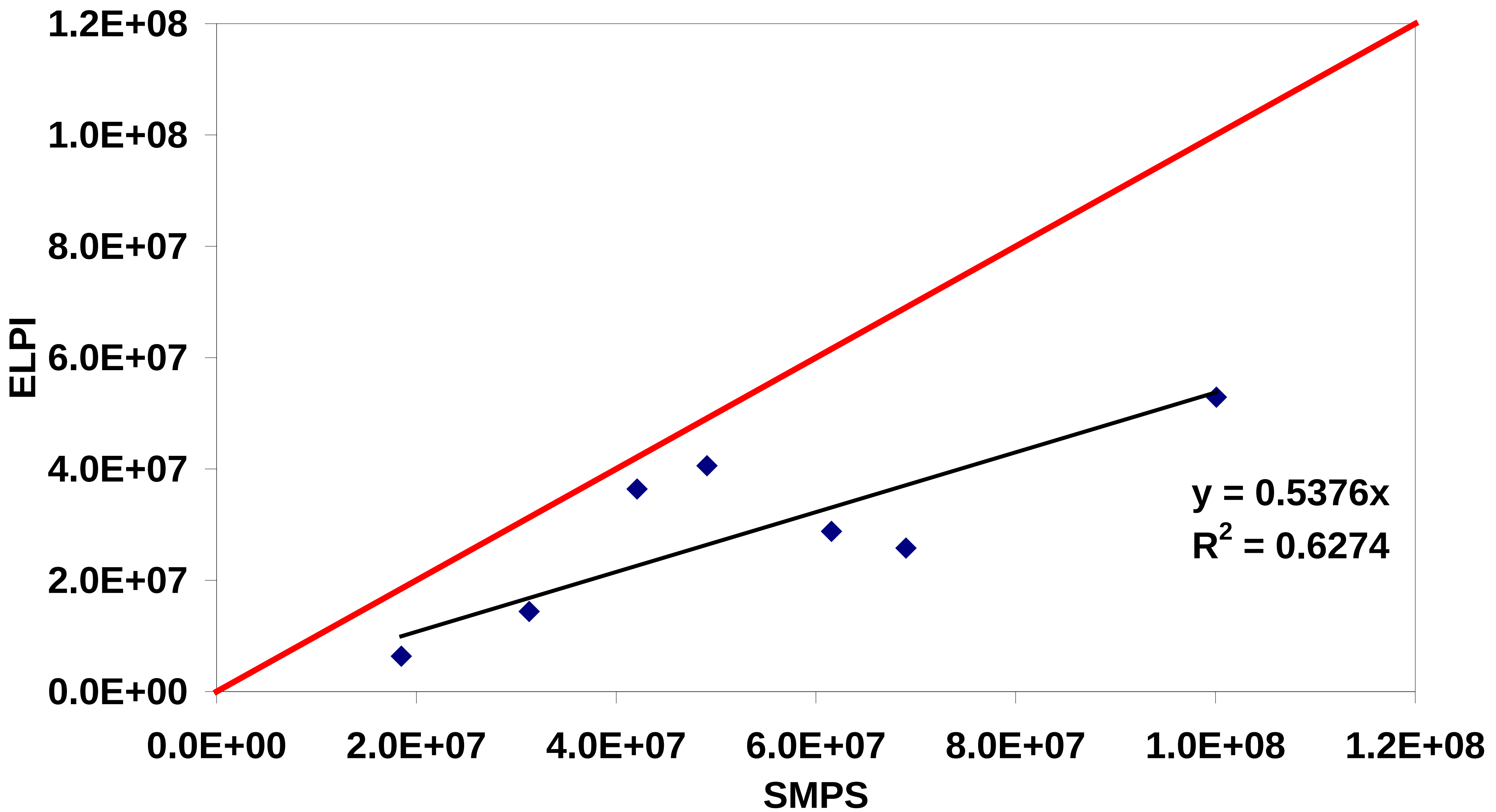
DOC out – Total Concentration (# / cm³) – SMPS vs CPC



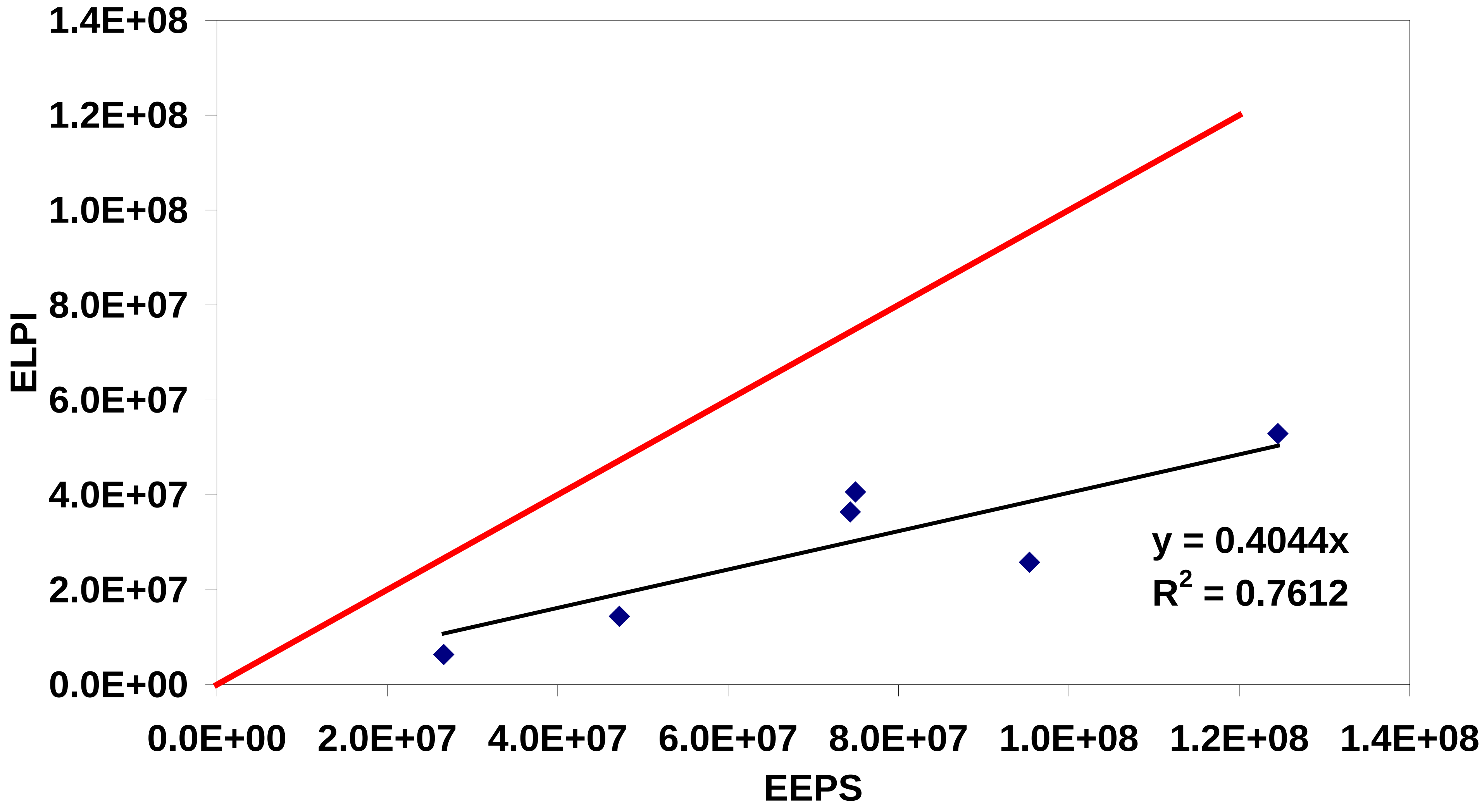
DOC out – Total Concentration (# / cm³) – EEPS vs SMPS



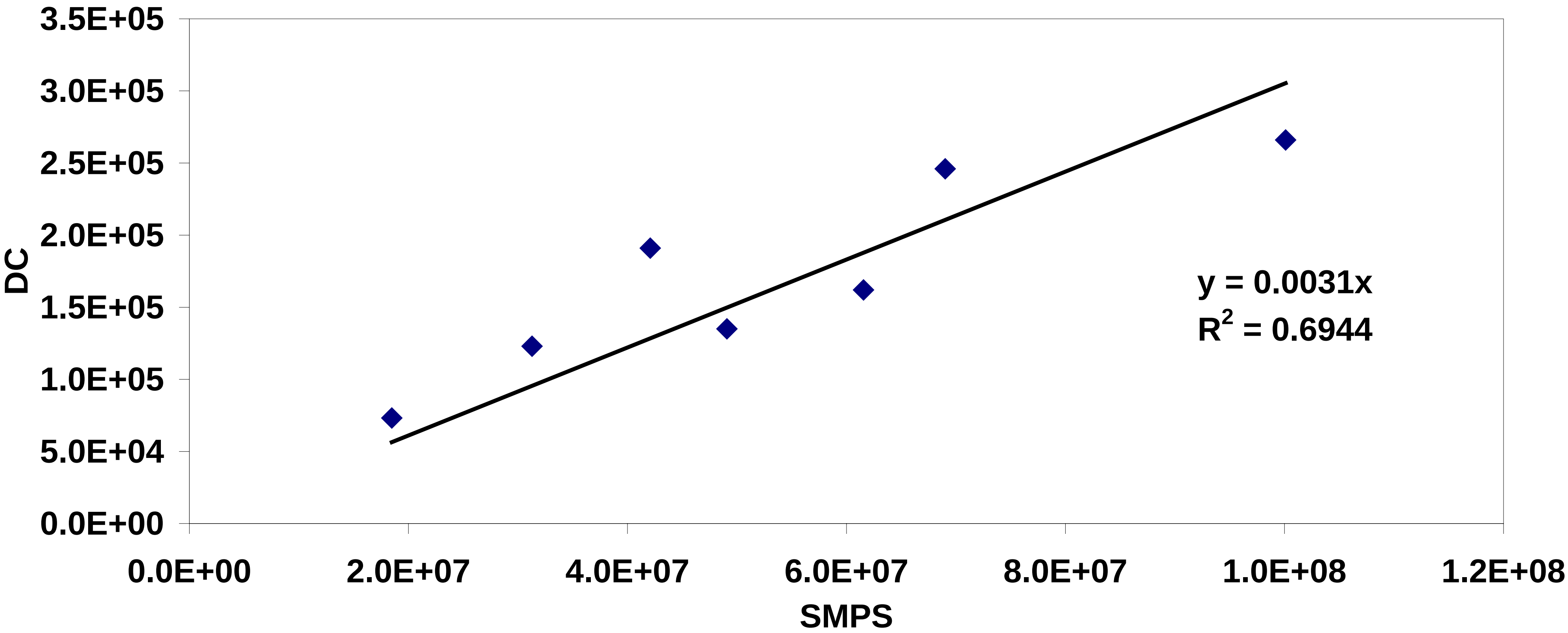
DOC out – Total Concentration (# / cm³) – ELPI vs SMPS



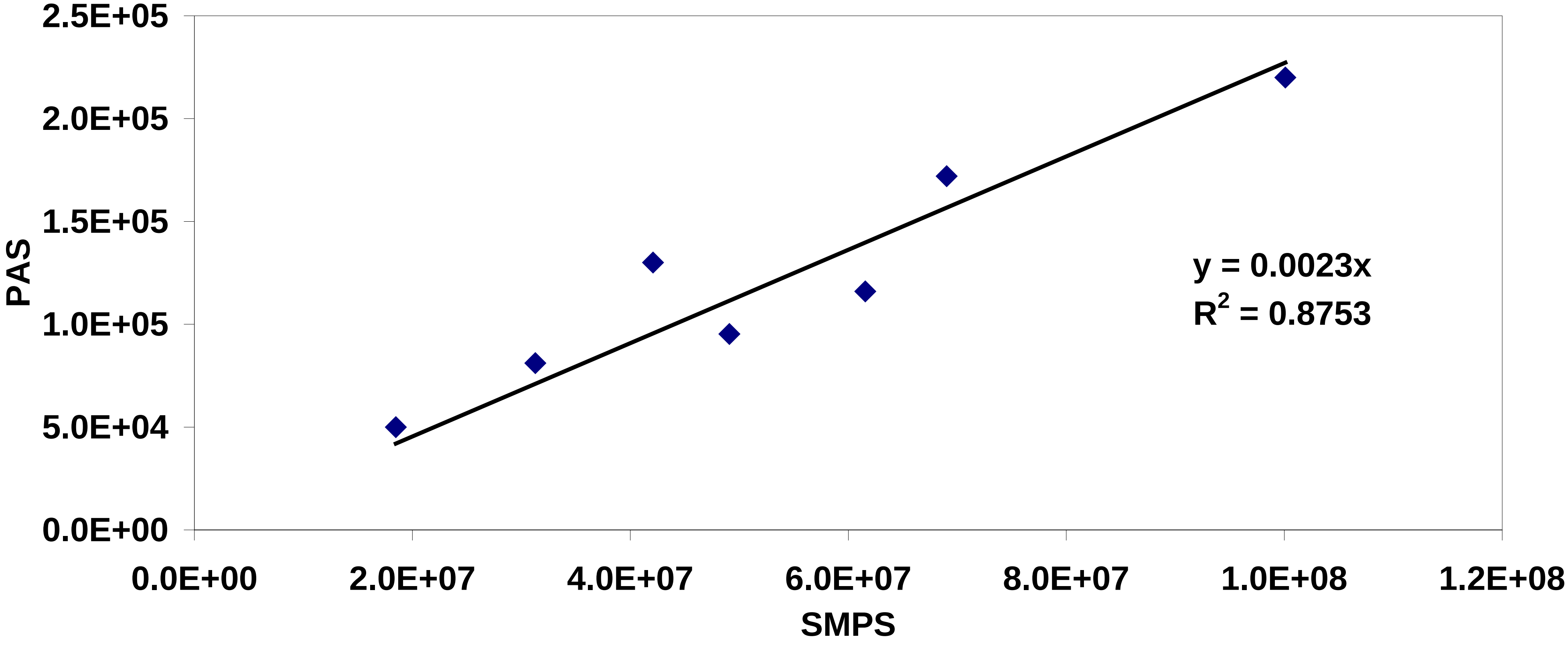
DOC out – Total Concentration (# / cm³) – ELPI vs EEPS



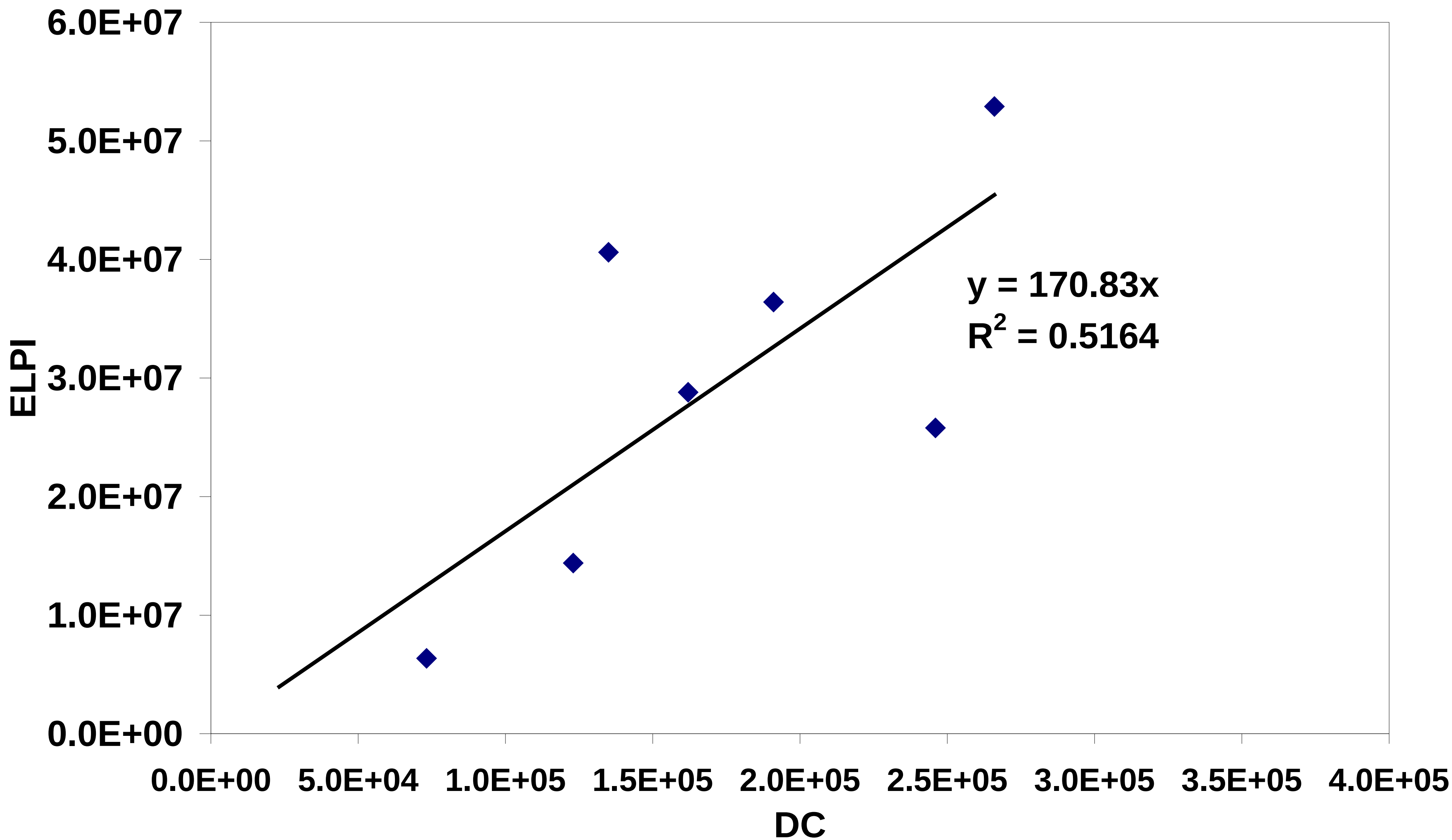
DOC out – Total Concentration (# / cm³) – SMPS vs DC



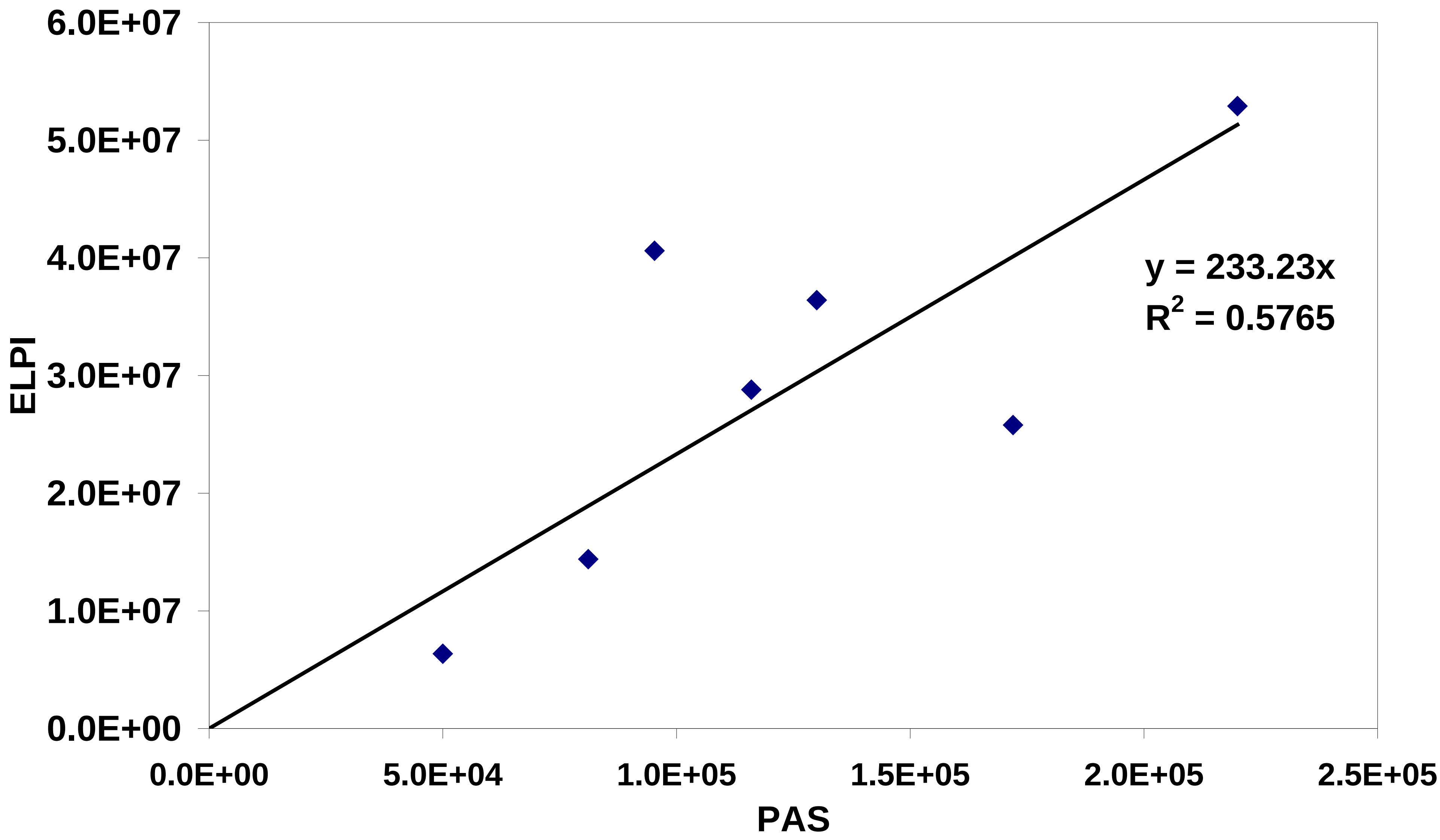
DOC out – Total Concentration (# / cm^3) – SMPS vs PAS



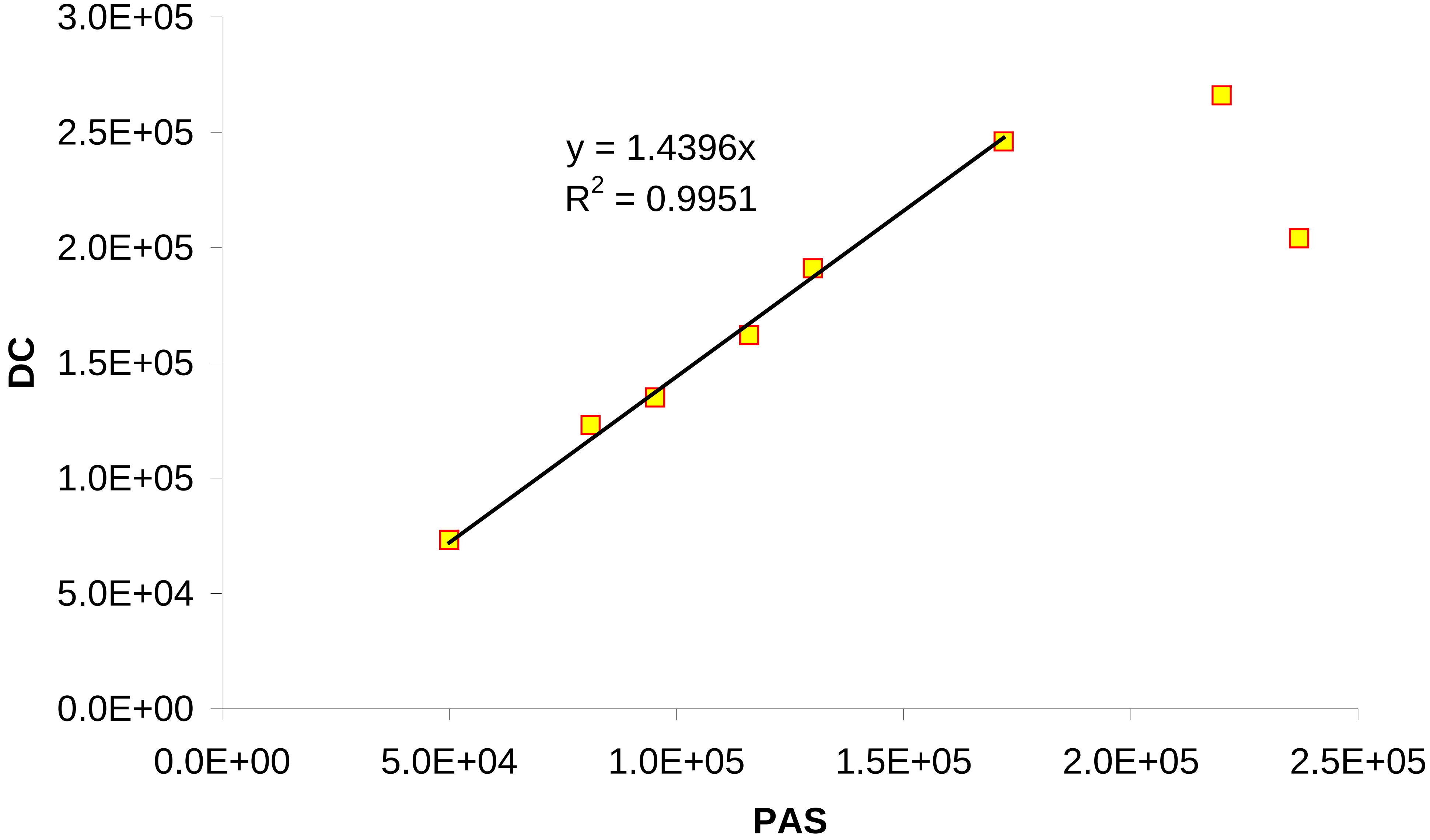
DOC out – Total Concentration (# / cm^3) – ELPI vs DC



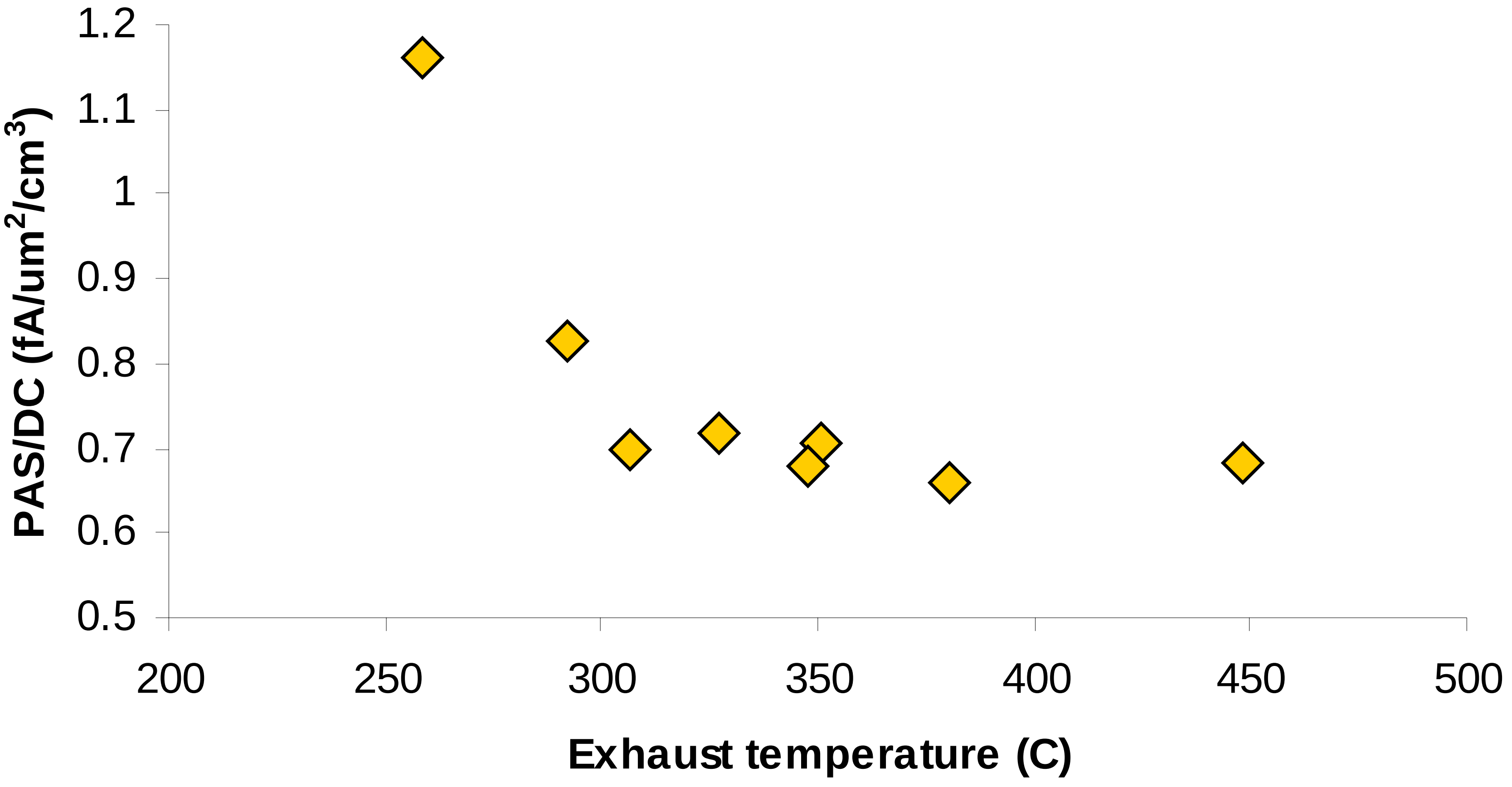
DOC out – Total Concentration (# / cm³) – ELPI vs PAS



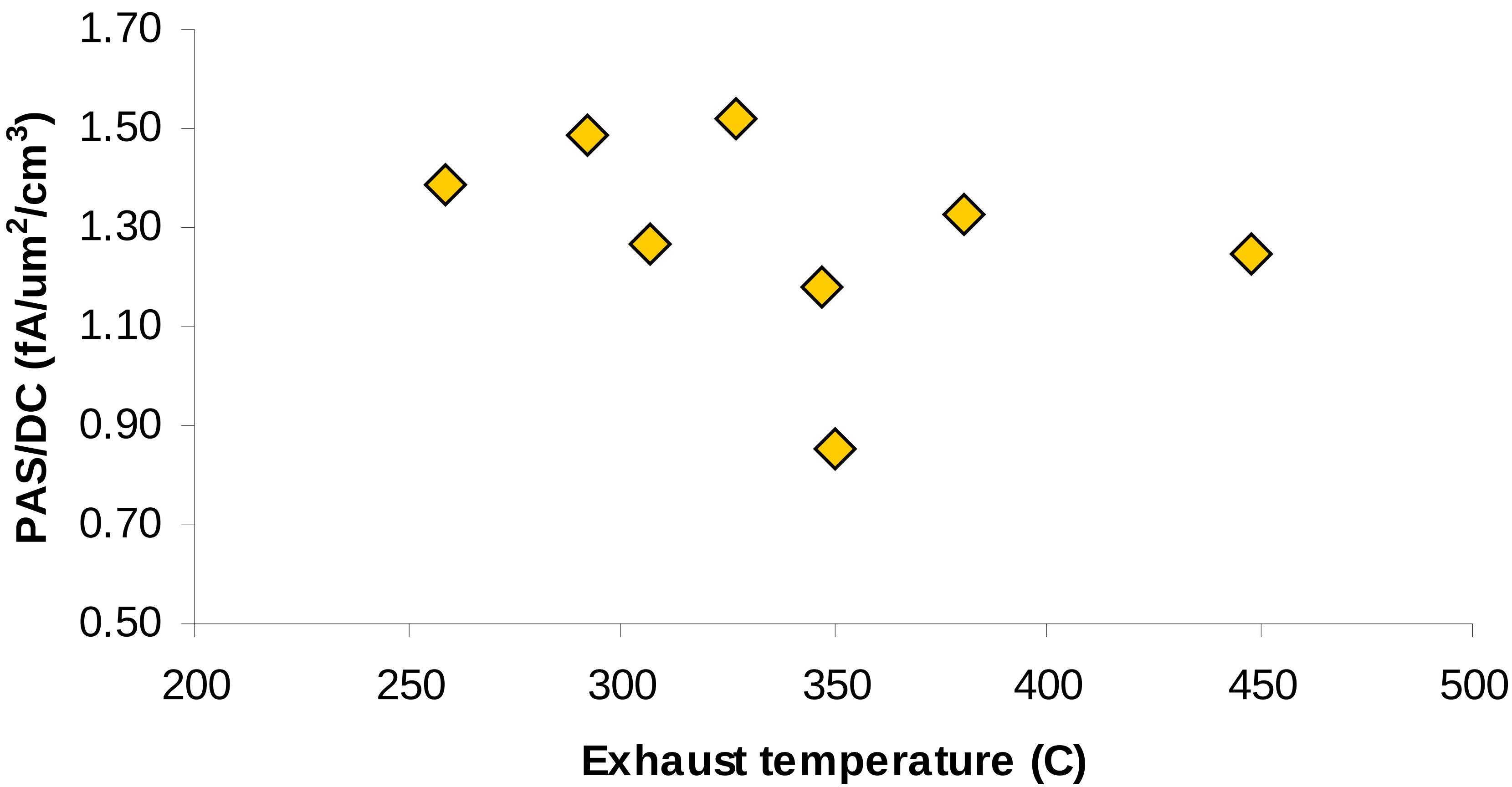
DOC out – DC vs PAS



DOC out – PAS / DC ratio

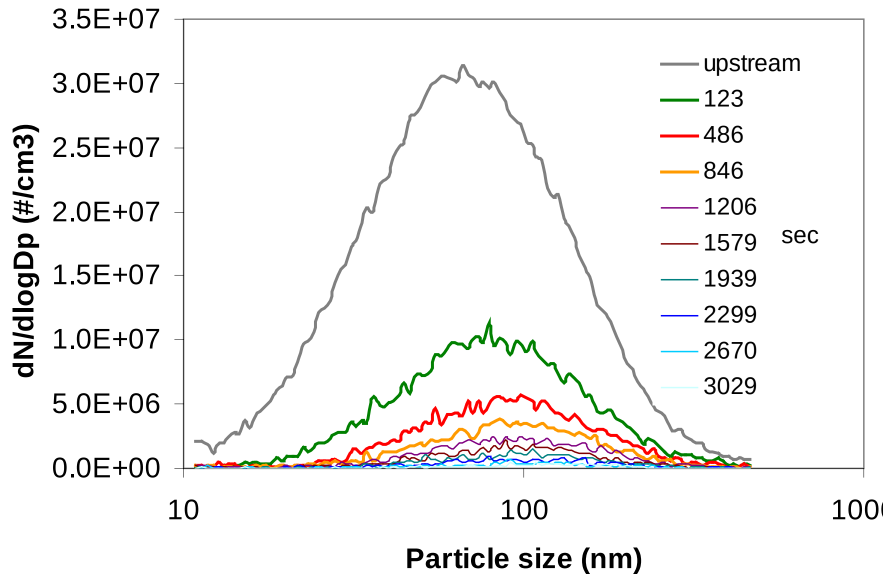


Engine out – PAS / DC ratio

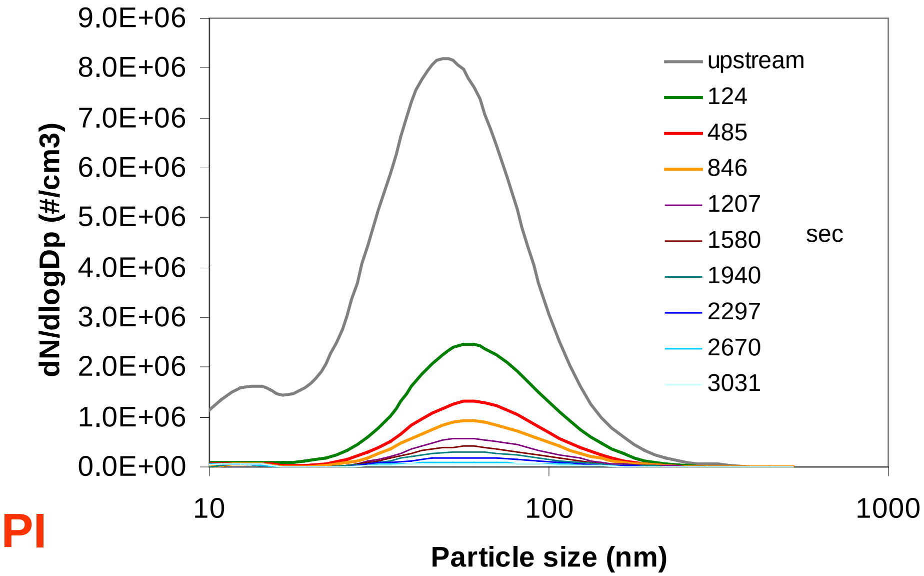


DPF-out Size Distribution Evolution at Steady State Engine Point

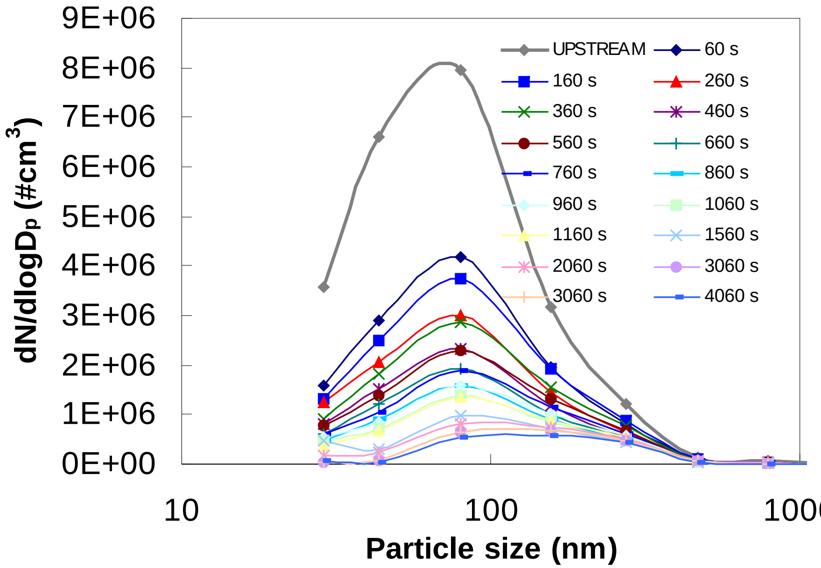
SMPS



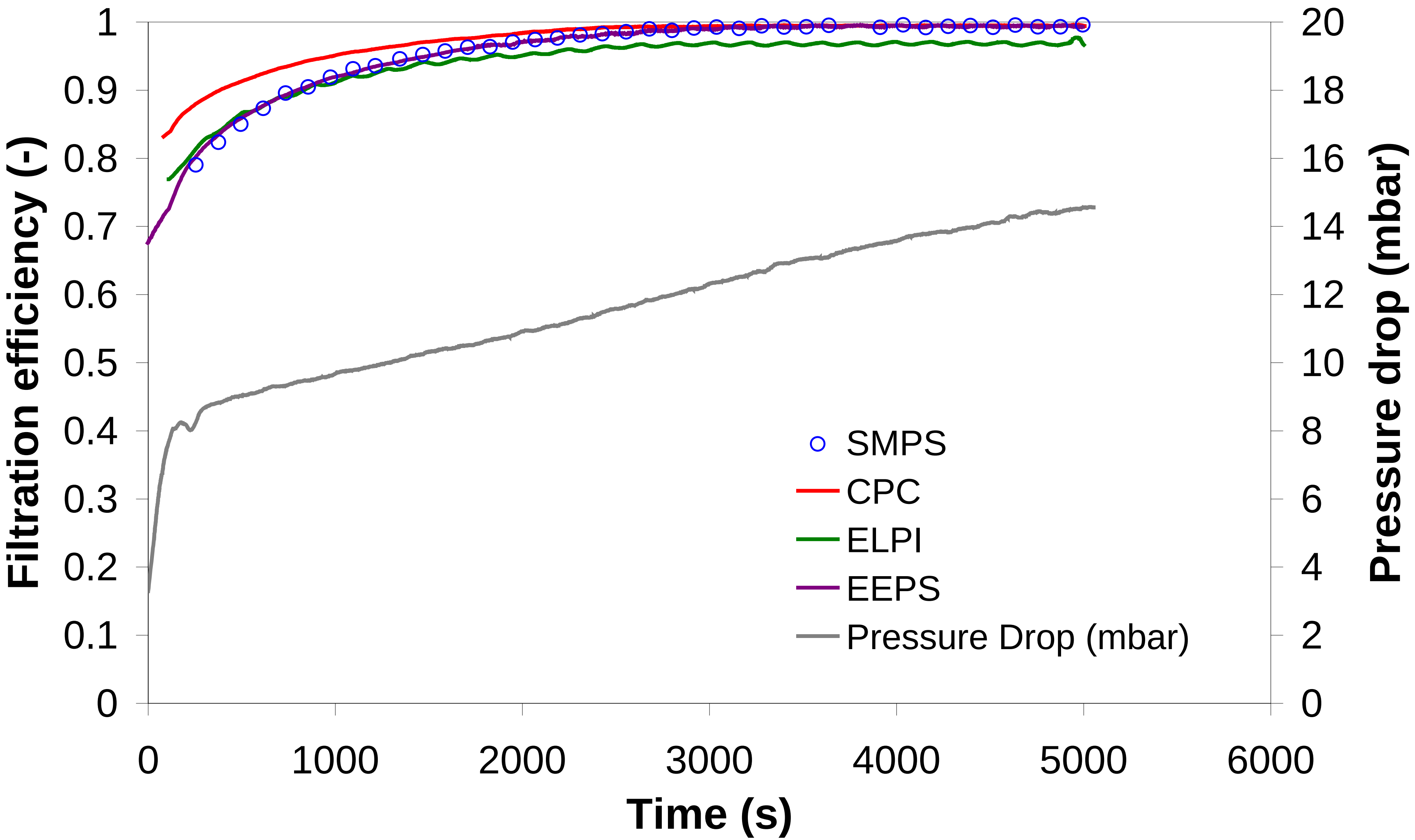
EEPS



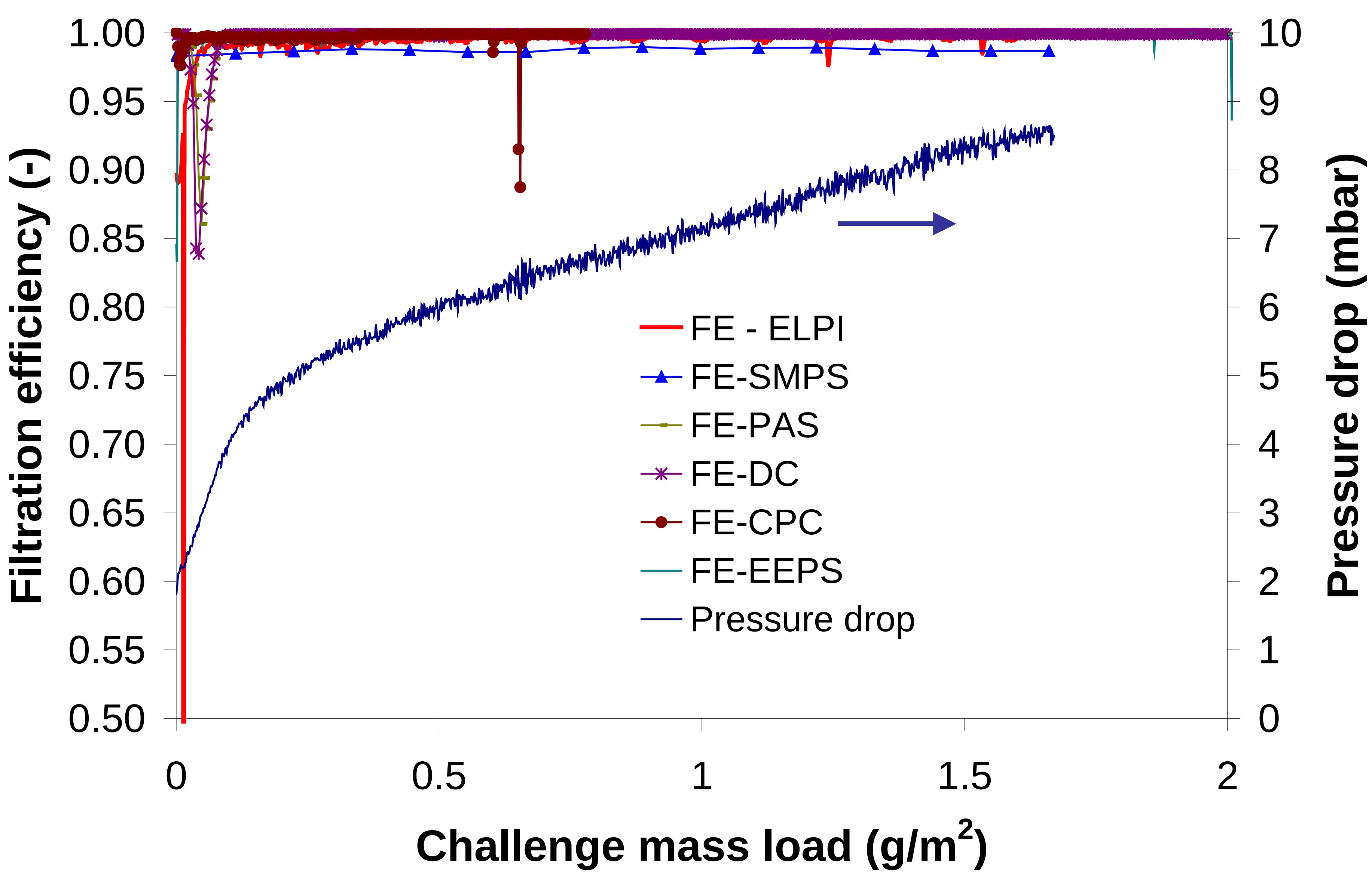
ELPI



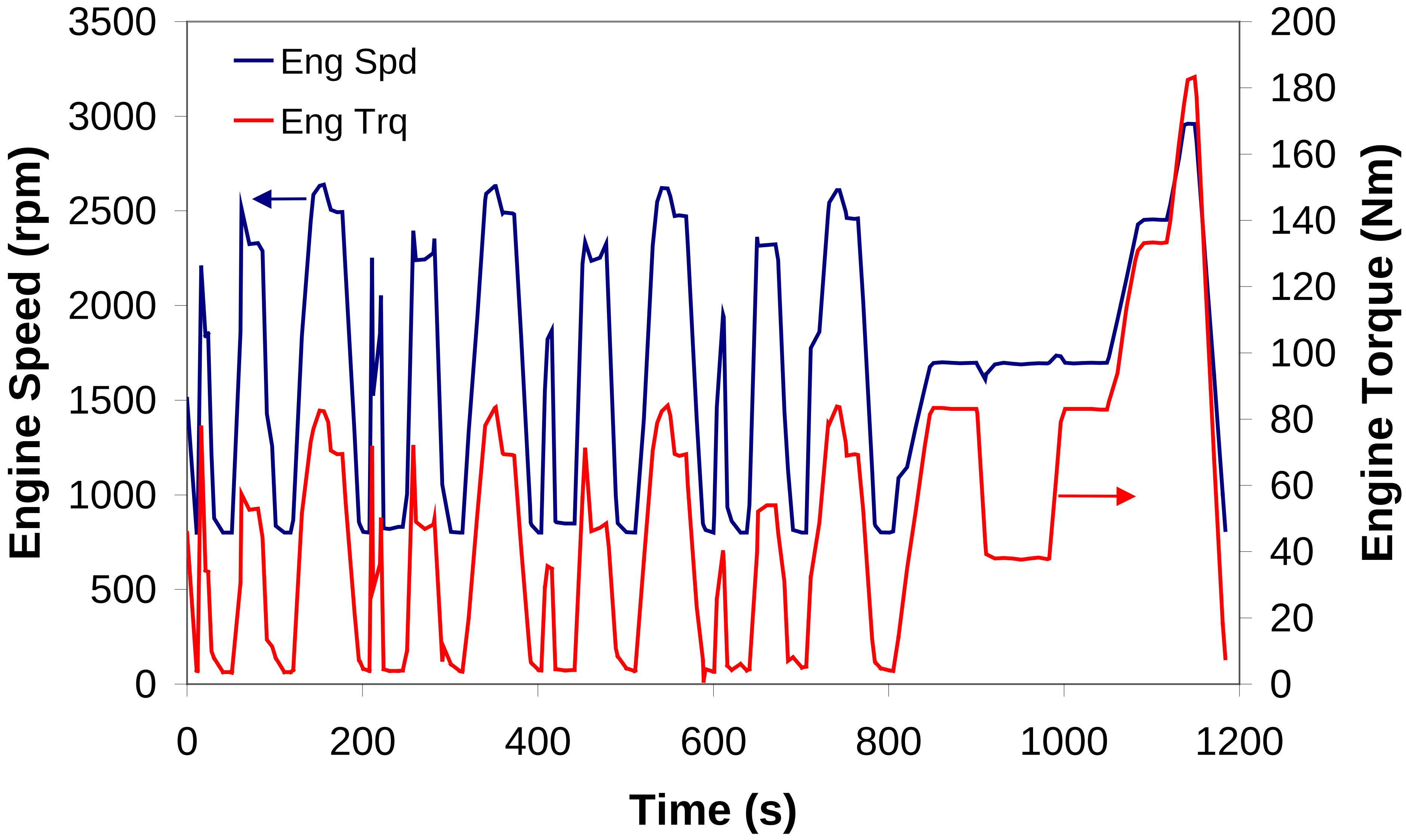
Filtration Efficiency at Steady State Engine Point



Filtration Efficiency at Steady State Engine Point

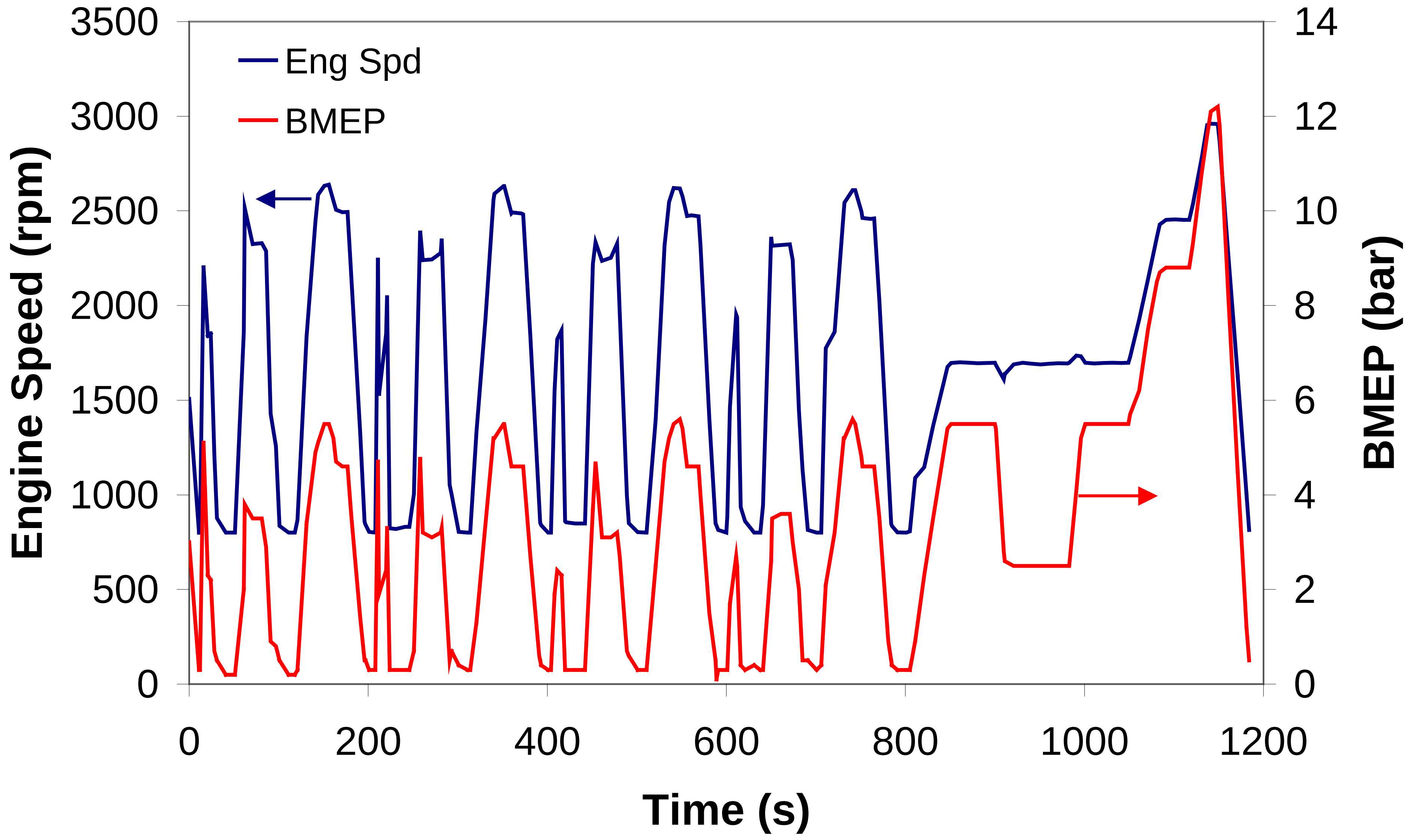


NEDC CYCLE



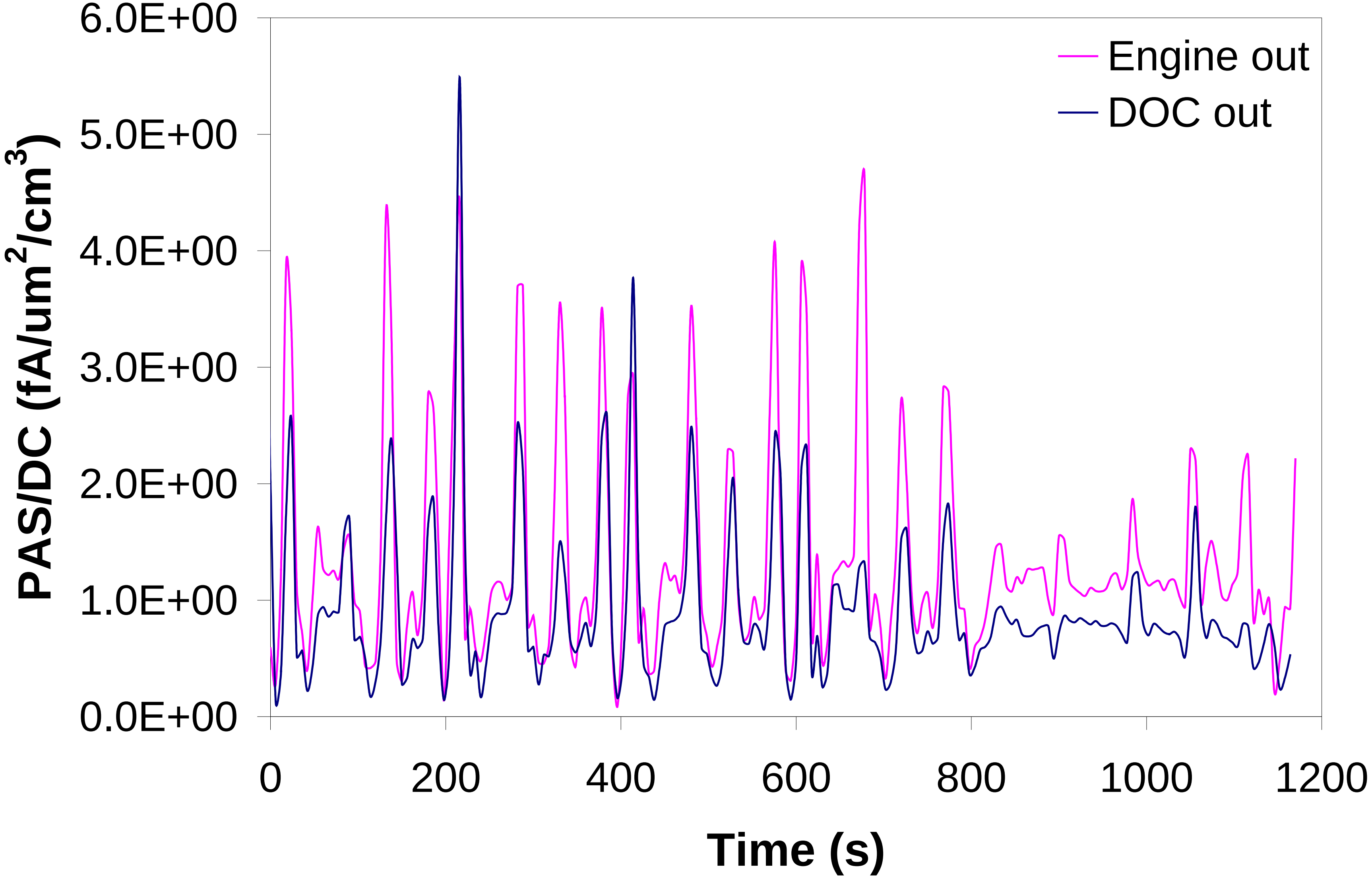
Eng Spd
Eng Trq
Engine Speed (rpm)
Engine Torque (Nm)
Time (s)
3500
3000
2500
2000
1500
1000
500
0
200
180
160
140
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200

NEDC CYCLE

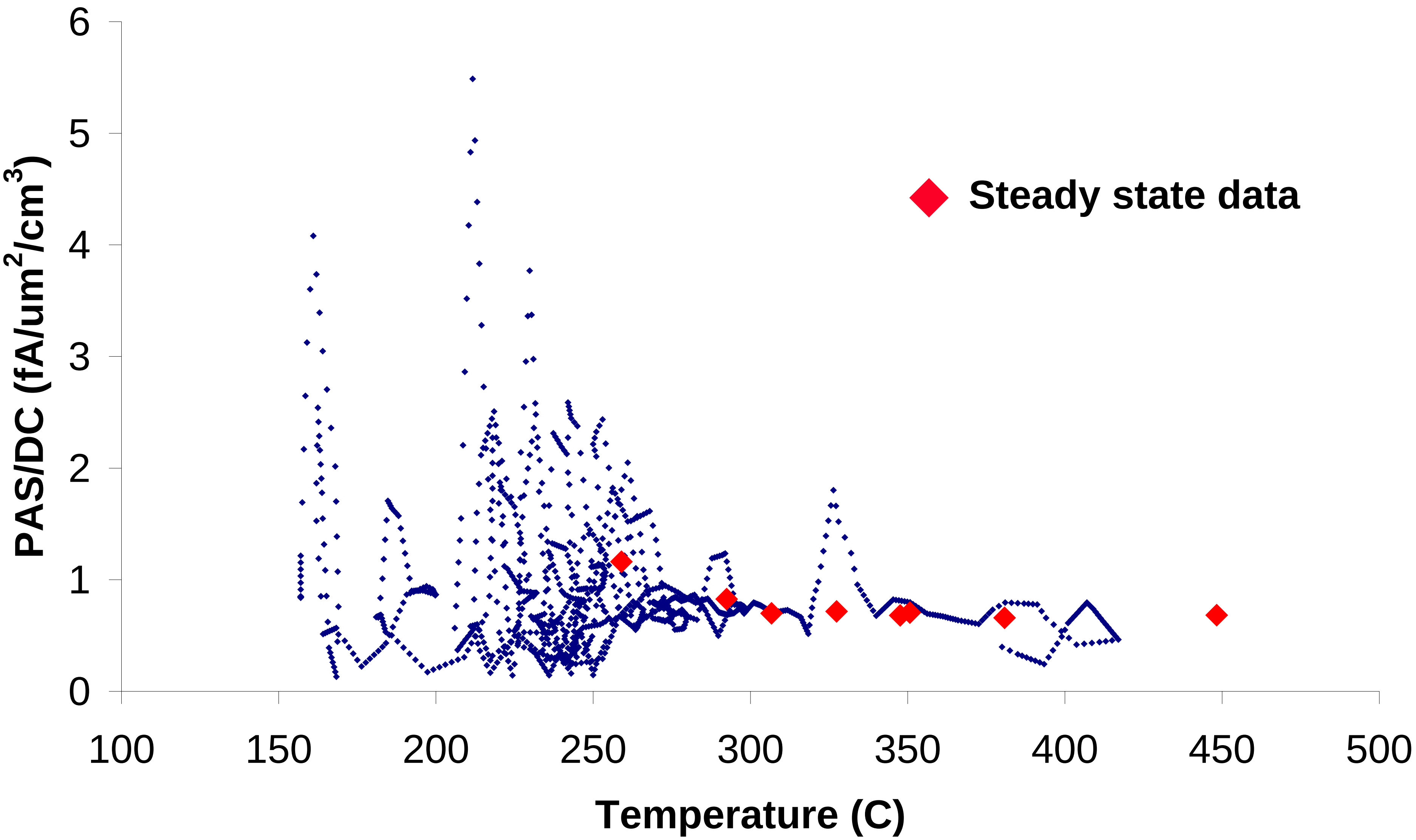


Eng Spd
BMEP
Engine Speed (rpm)
BMEP (bar)
Time (s)
3500
3000
2500
2000
1500
1000
500
0
14
12
10
8
6
4
2
0
0
200
400
600
800
1000
1200

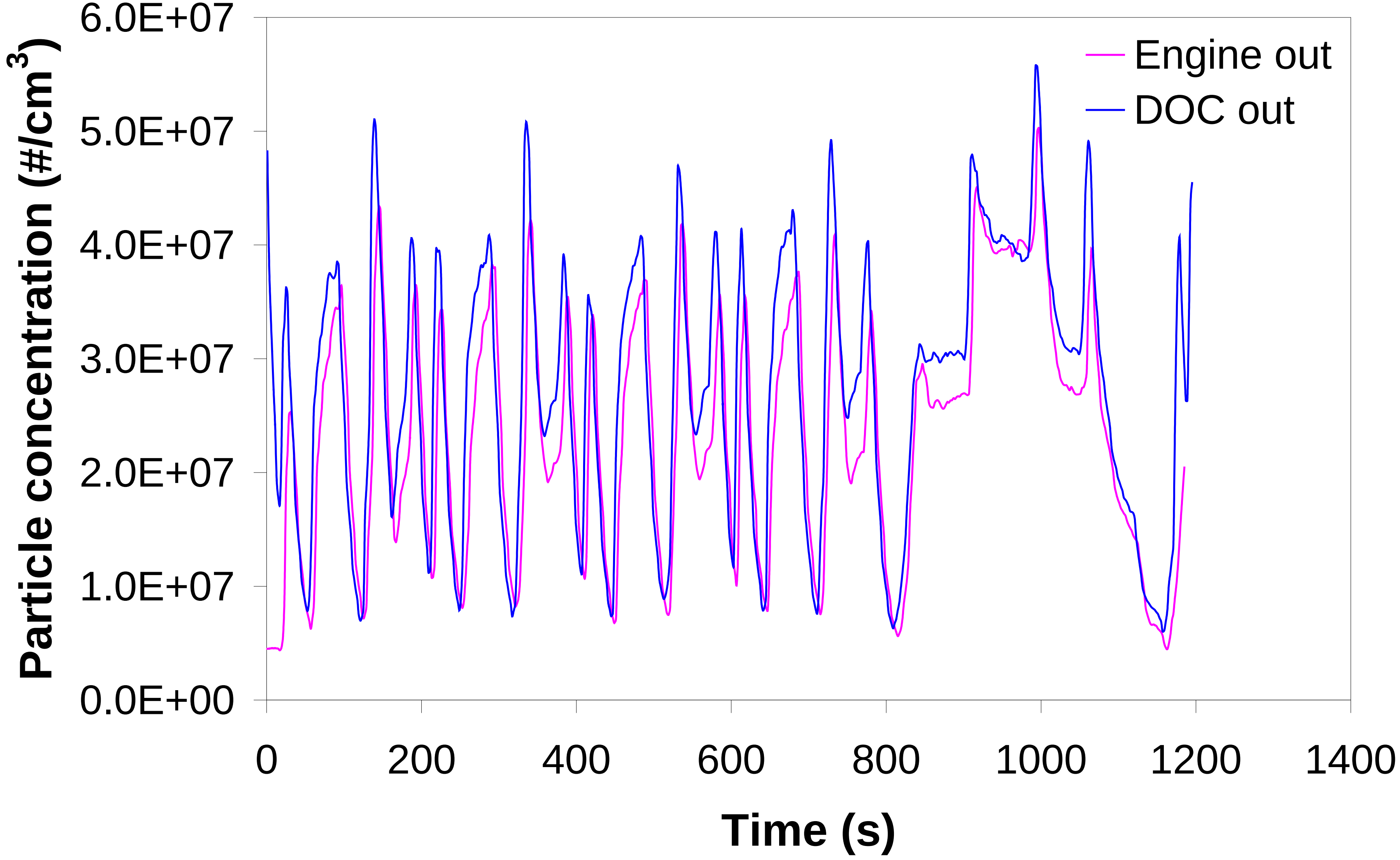
DOC out – PAS / DC ratio



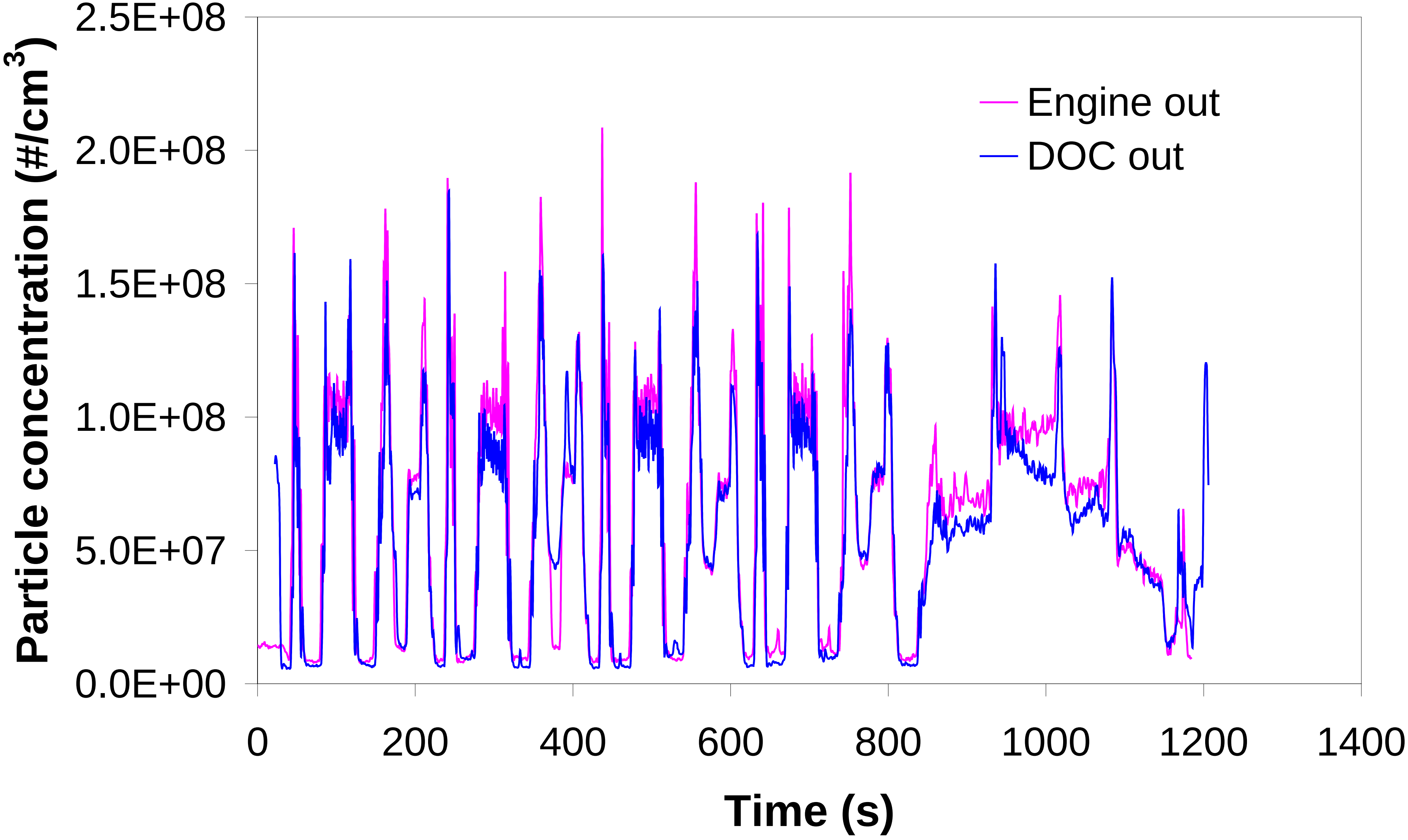
DOC out – PAS / DC ratio



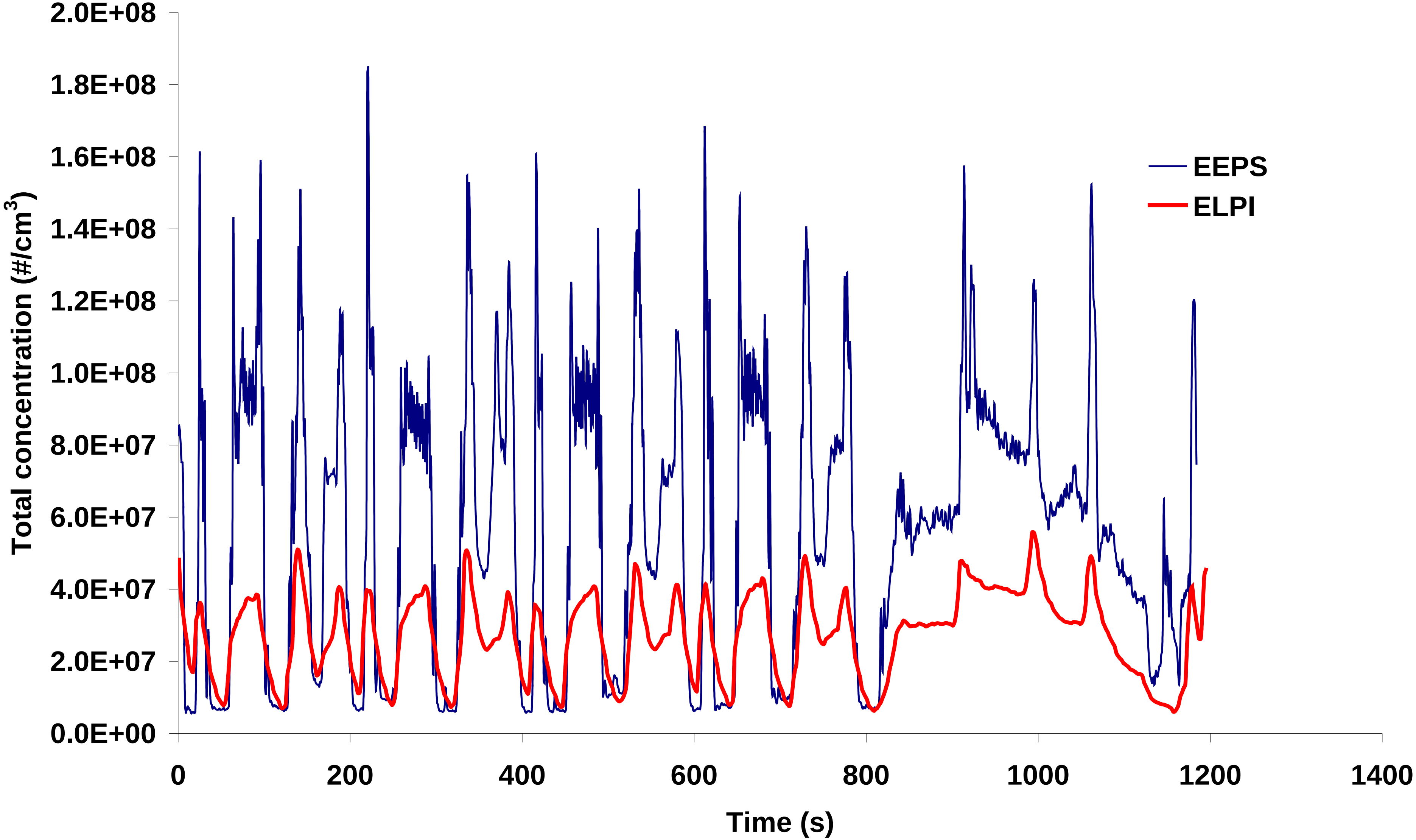
Effect of DOC– Total Concentration (# / cm³) – ELPI



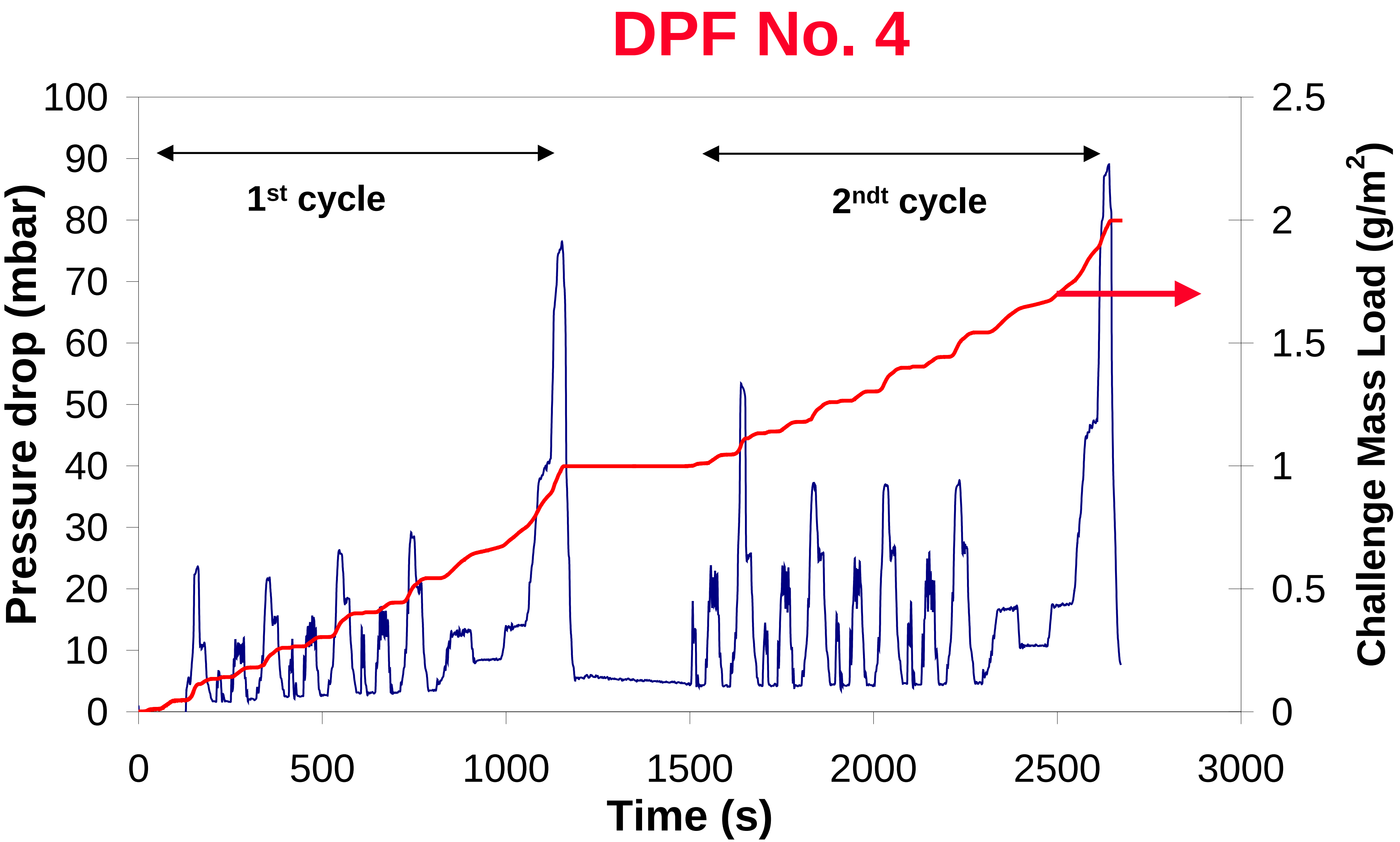
Effect of DOC– Total Concentration (# / cm³) – EEPS



NEDC– Total Concentration (# / cm^3) – EEPS vs. ELPI

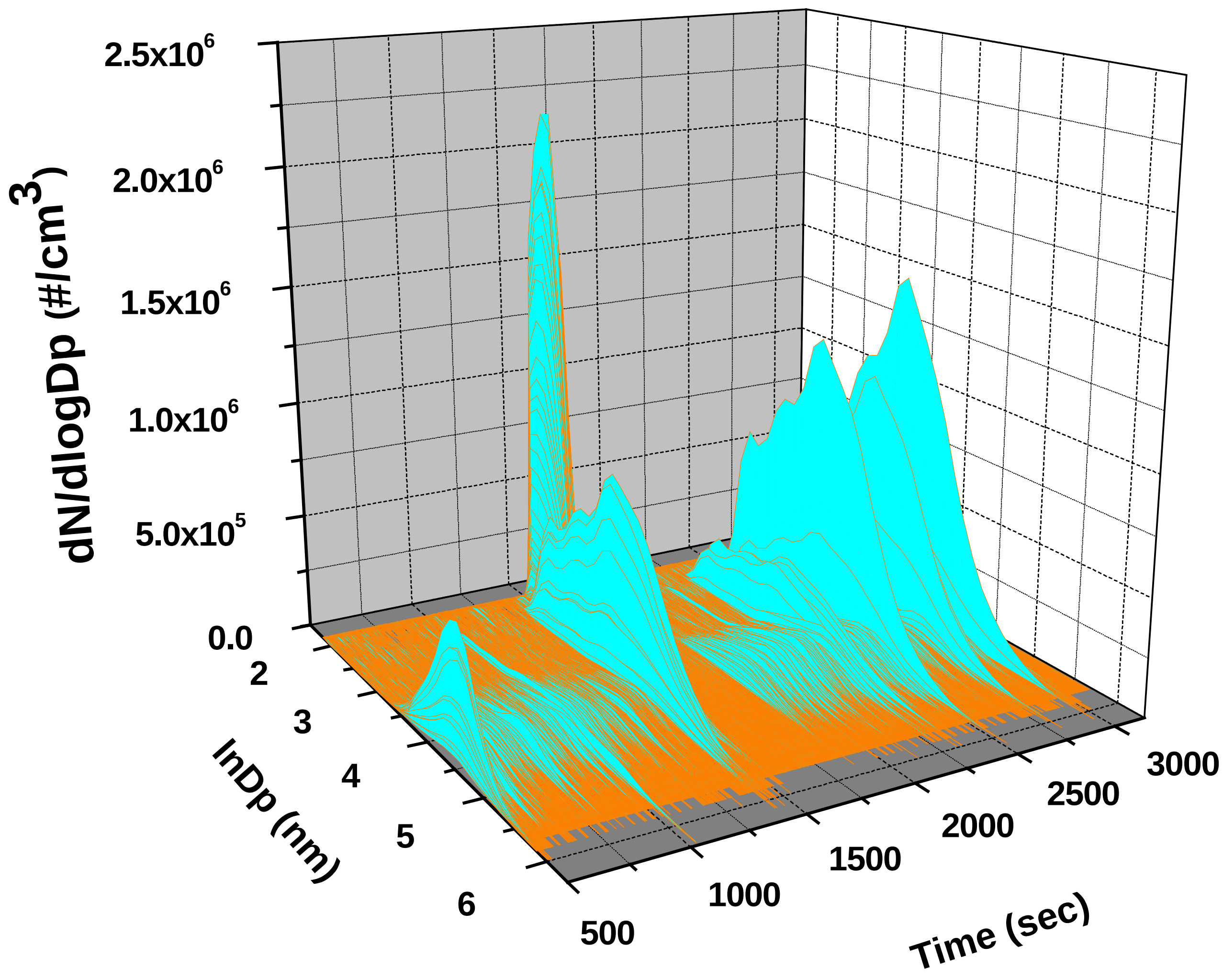


NEDC– Pressure drop and Challenge Mass Load



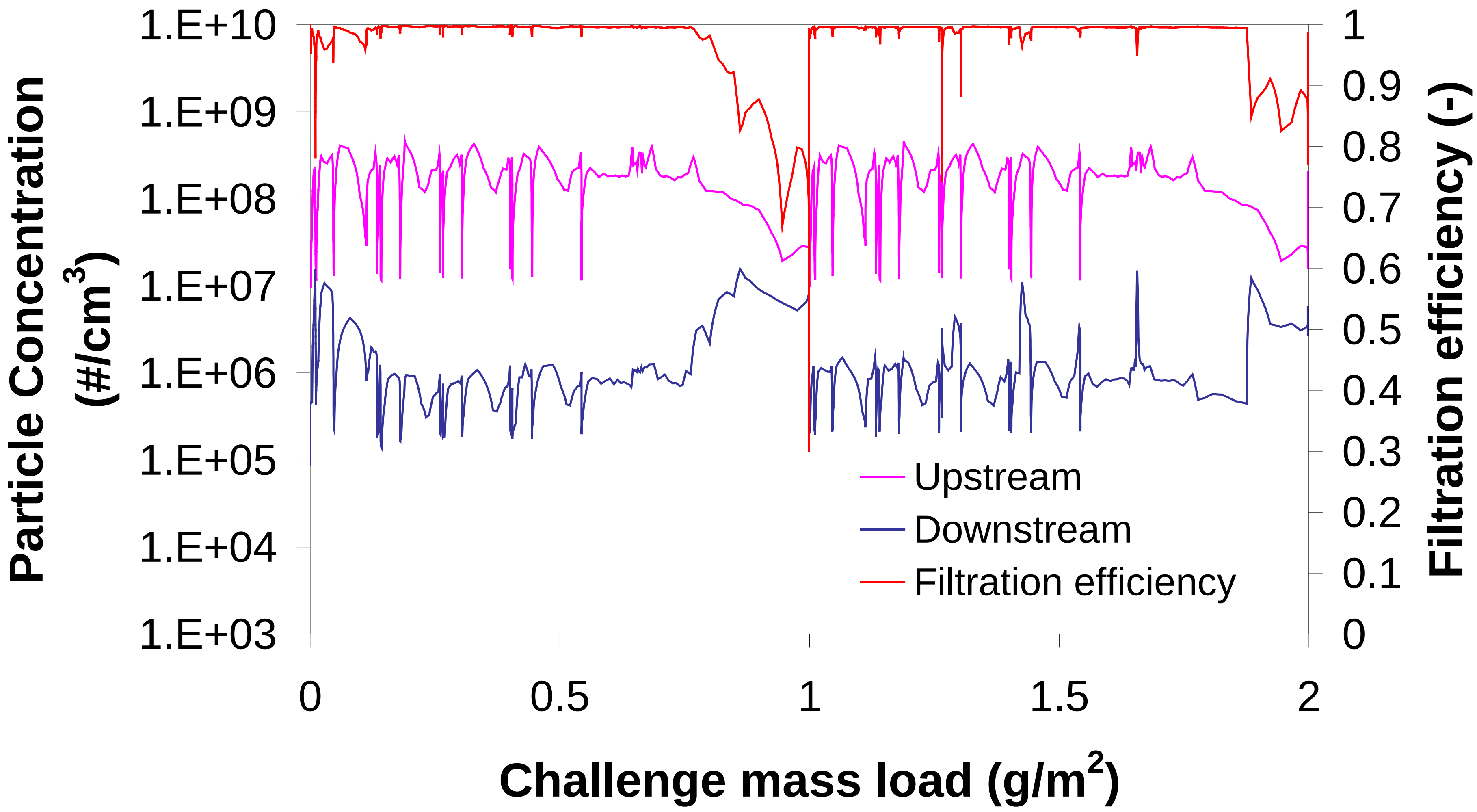
NEDC– EEPS size distribution evolution

DPF No. 4



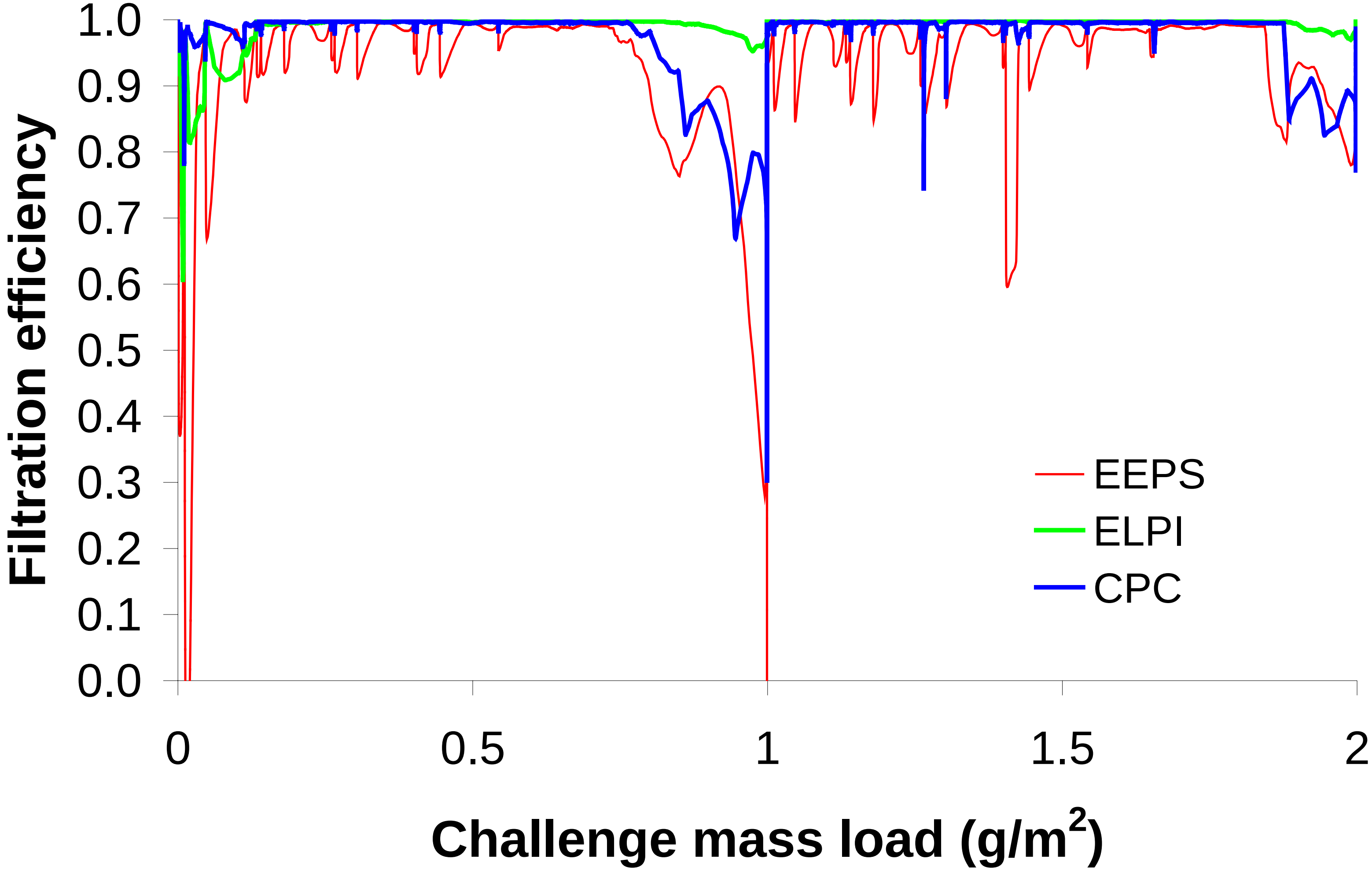
NEDC– CPC Filtration Efficiency vs. Mass Load

DPF No. 4



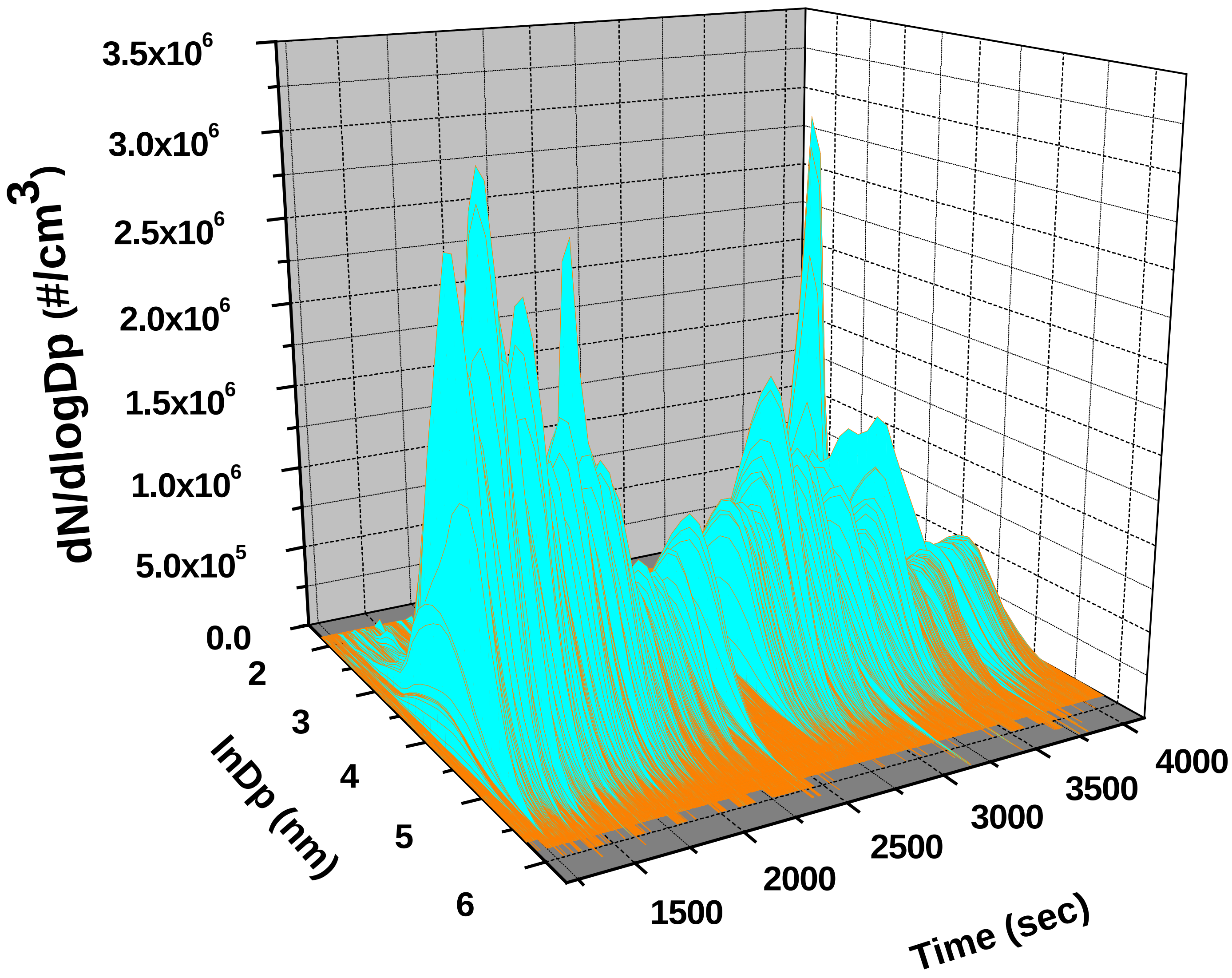
NEDC– Filtration Efficiency vs. Mass Load

DPF No. 4



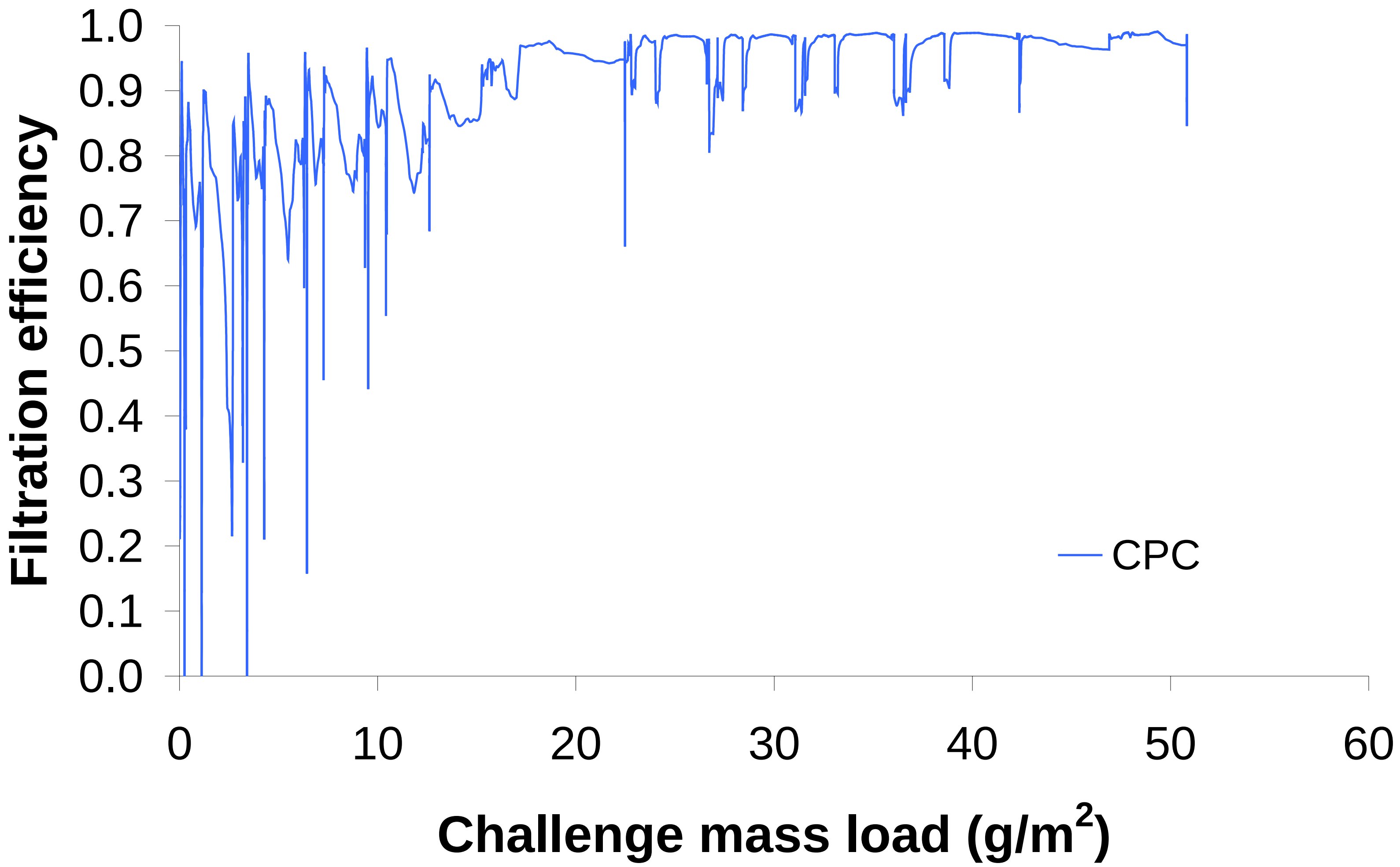
NEDC– EEPS size distribution evolution

DPF No. 5



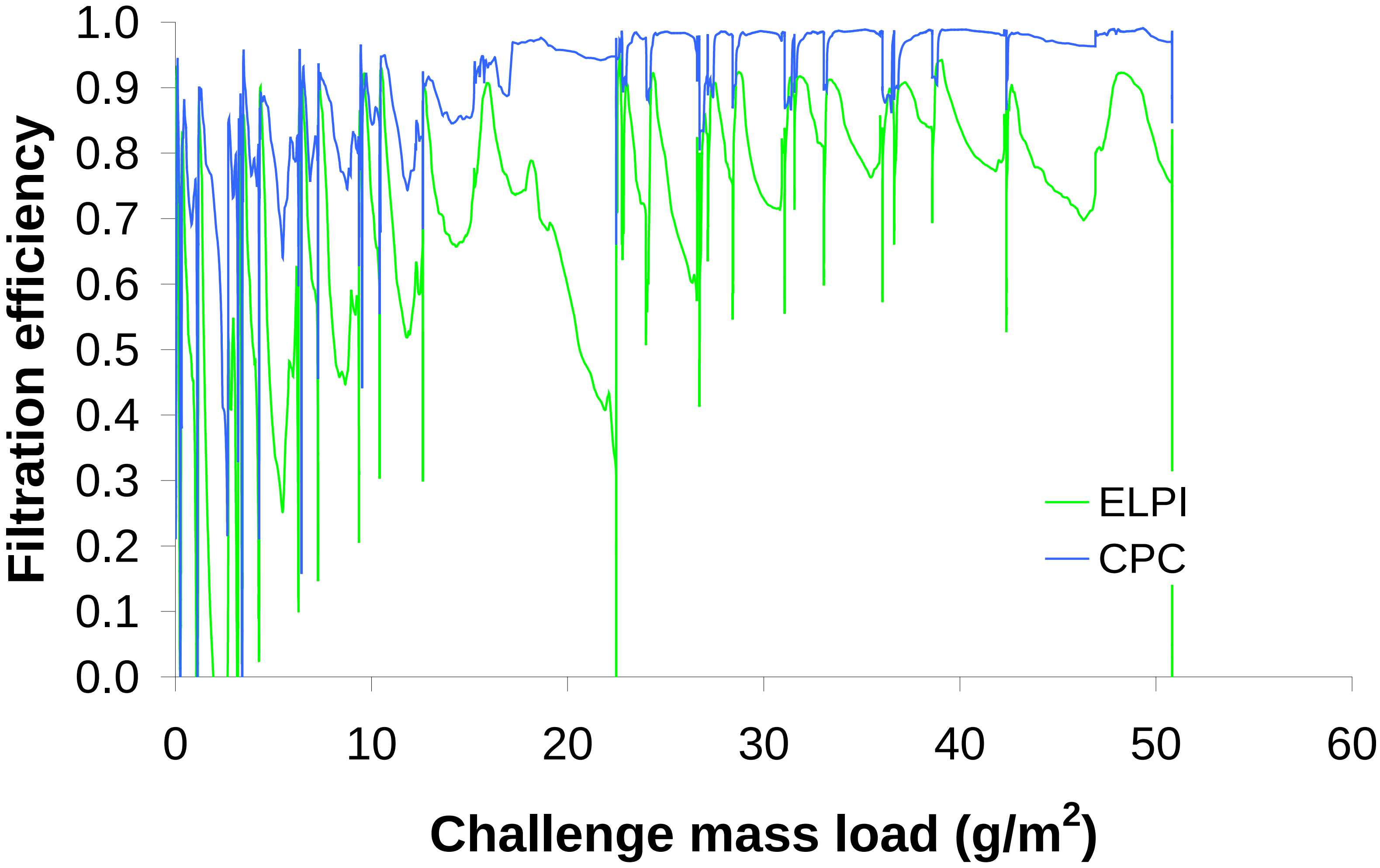
NEDC– Filtration Efficiency vs. Mass Load

DPF No. 5



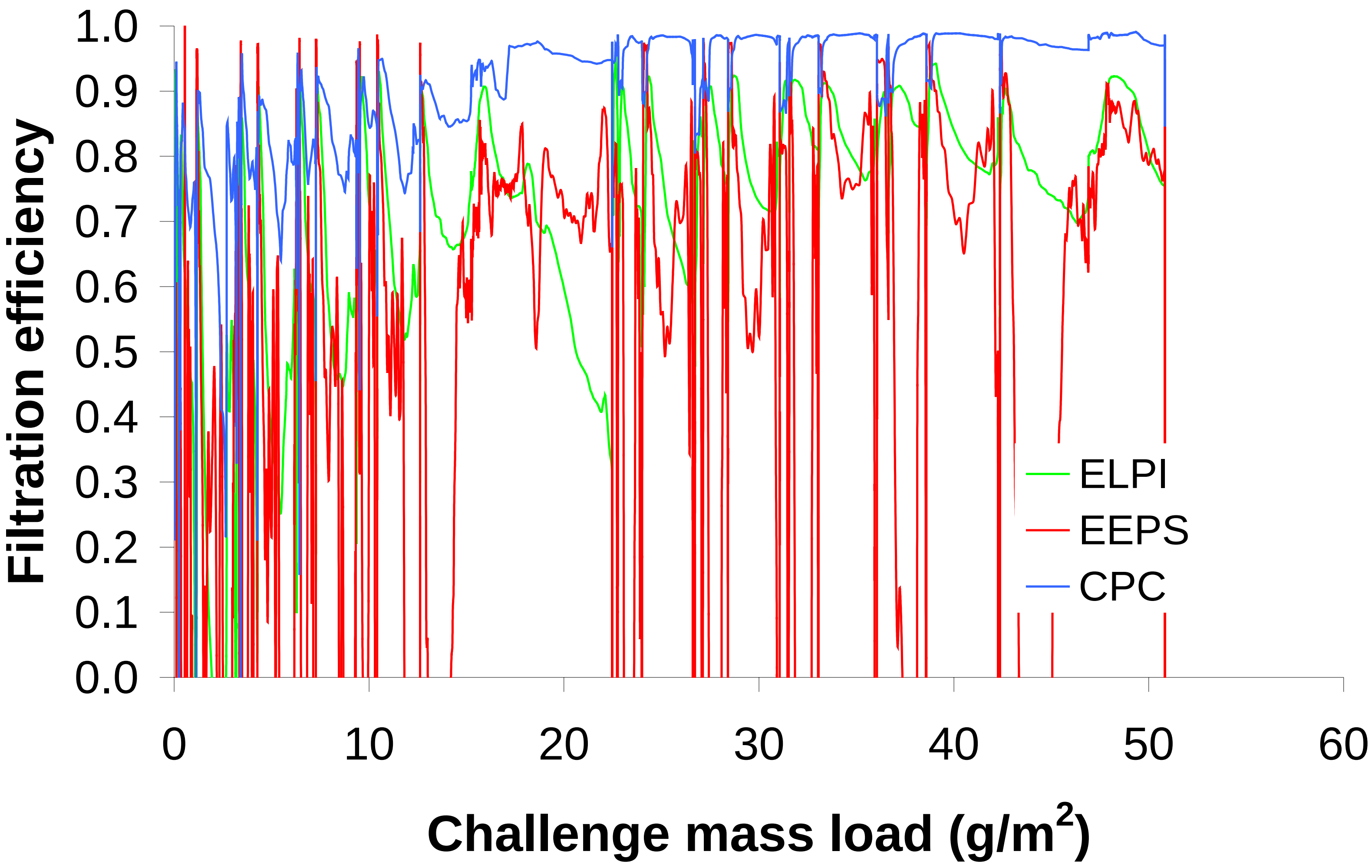
NEDC– Filtration Efficiency vs. Mass Load

DPF No. 5



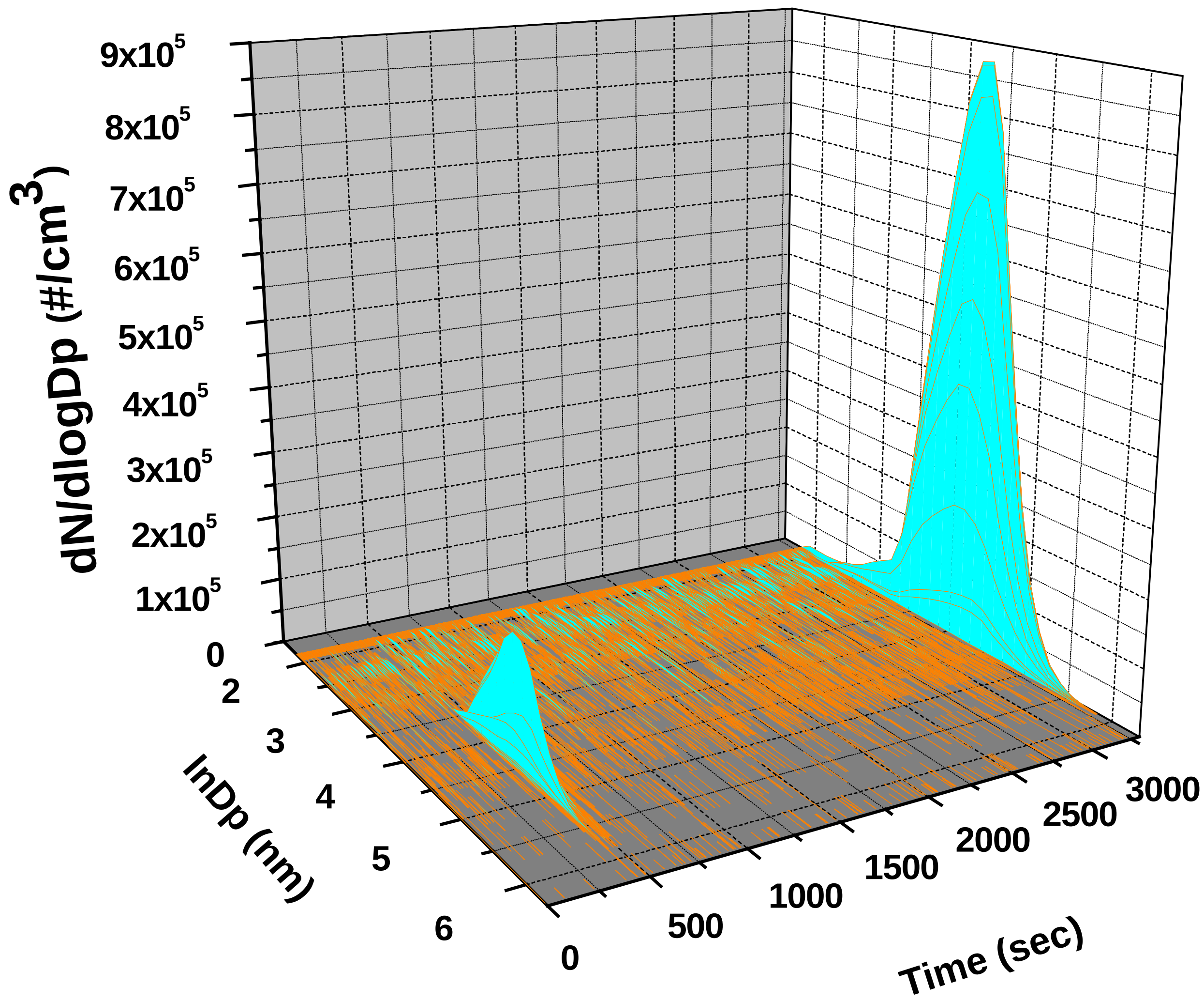
NEDC– Filtration Efficiency vs. Mass Load

DPF No. 5



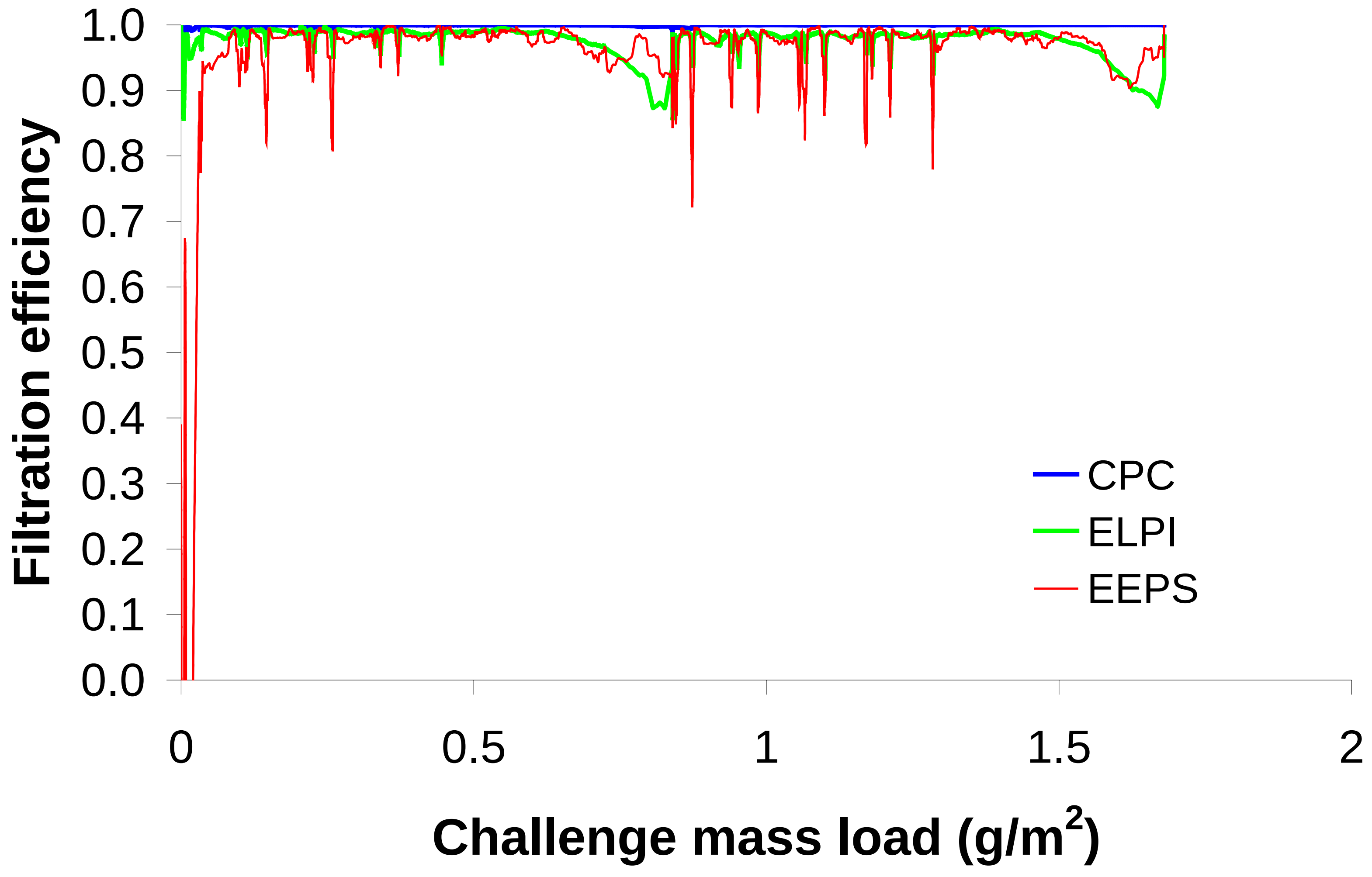
NEDC– EEPS size distribution evolution

DPF No. 1



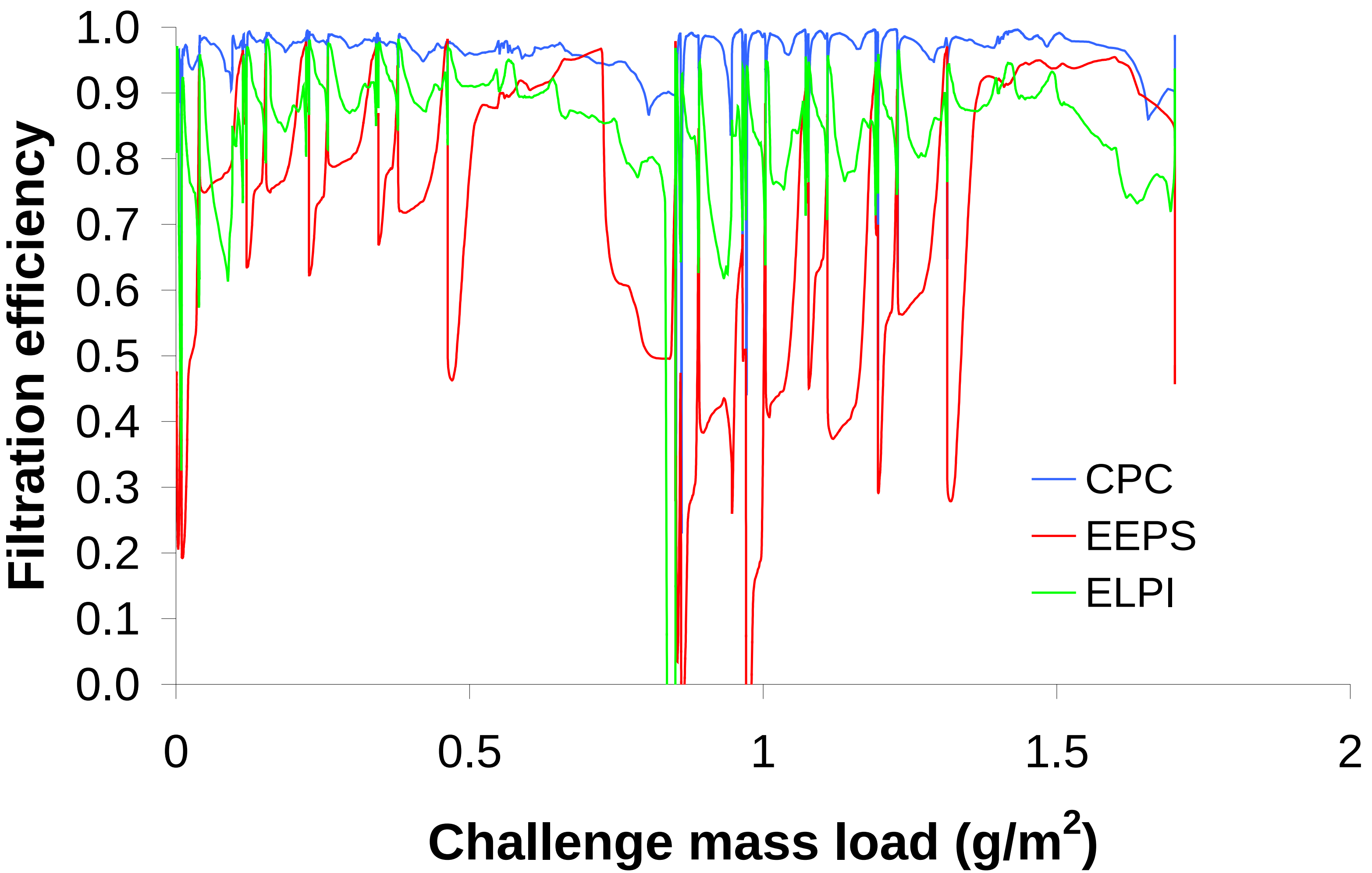
NEDC– Filtration Efficiency vs. Mass Load

DPF No. 1



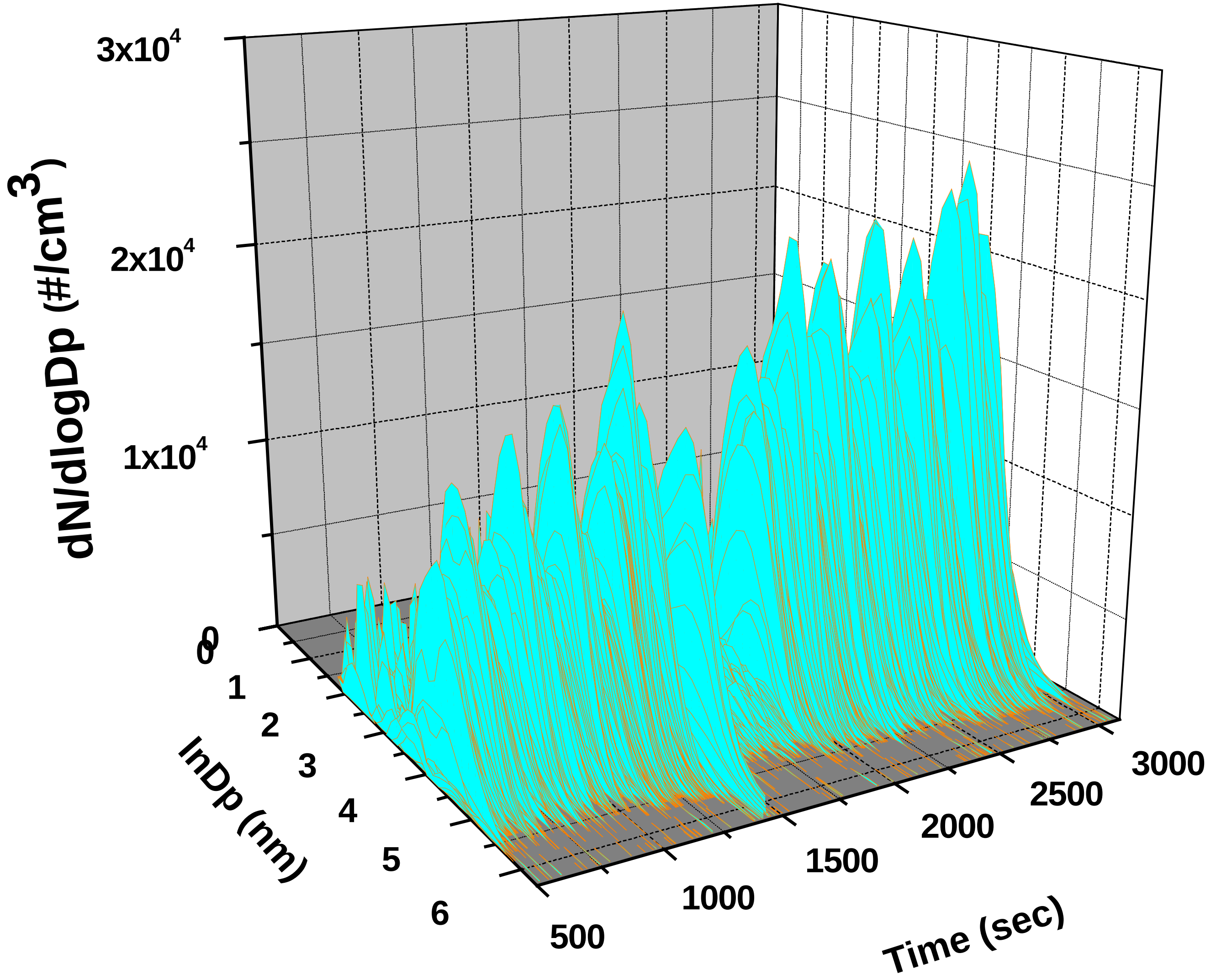
NEDC– Filtration Efficiency vs. Mass Load

DPF No. 2



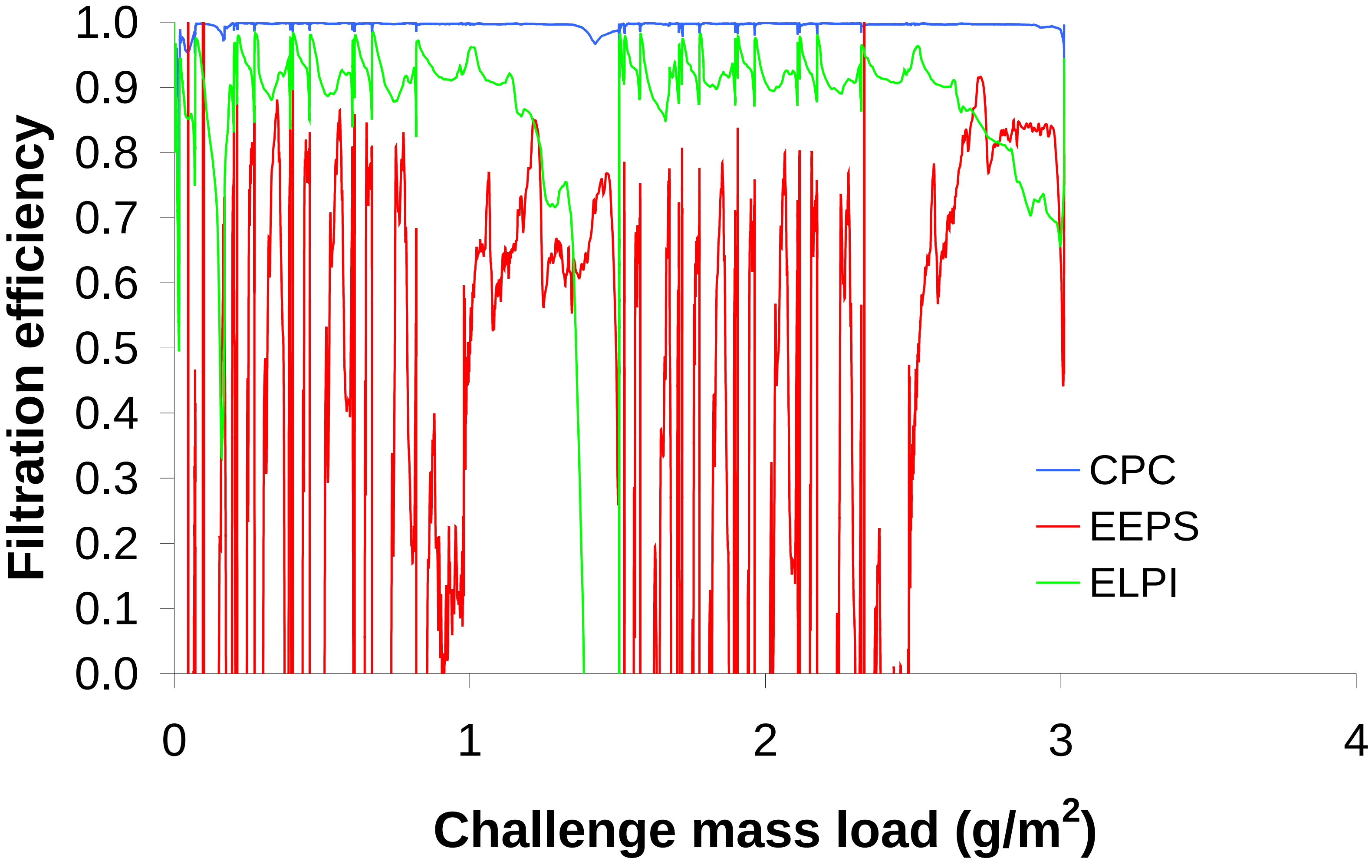
NEDC– EEPS size distribution evolution

DPF No. 3

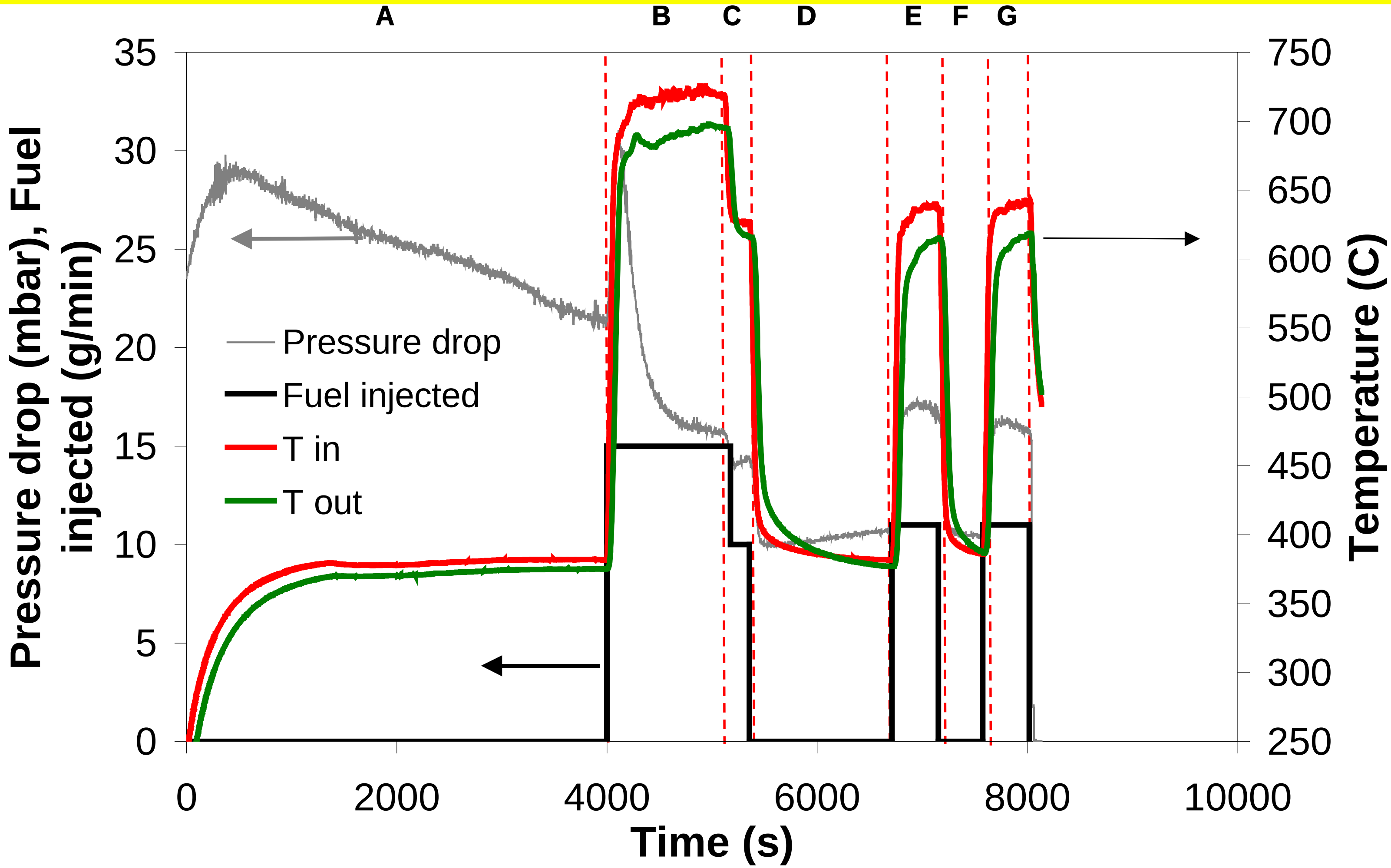


NEDC– Filtration Efficiency vs. Mass Load

DPF No. 3



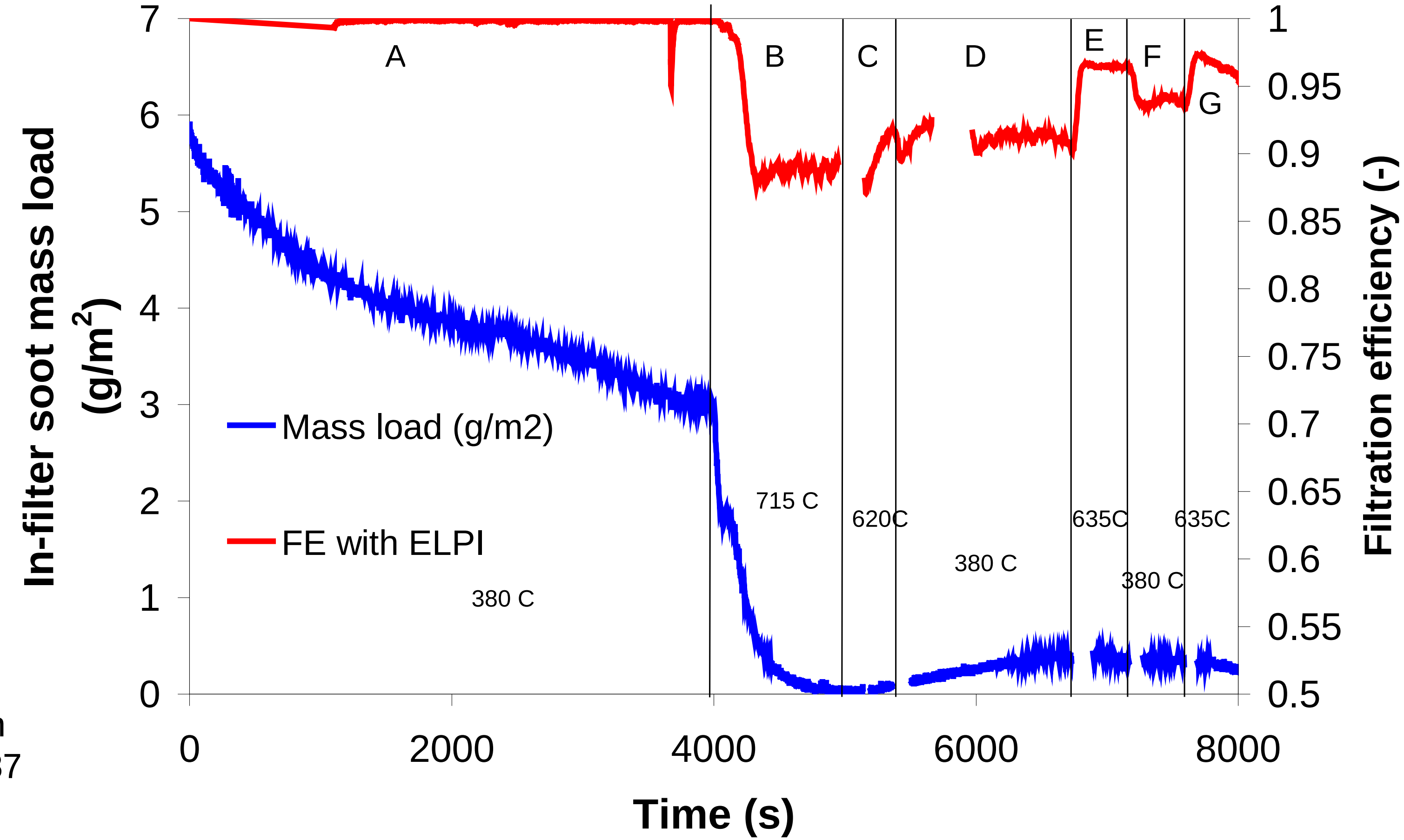
FILTER REGENERATION TEST



Step A lasted 4000 s. During this step a NOx assisted partial filter regeneration occurred. At time=4000 s, fuel was injected upstream of the DOC at a constant rate of 15 g/min. This raised the filter inlet temperature to 720 C. This step lasted for 1100 s and led to a complete filter regeneration (Step B). The fuel injection continued for 100 s more, but at a smaller fuel injection rate (10 g/min ; step C). Further fuel injections were performed in following steps (steps E and G).

FILTRATION EFFICIENCY DURING REGENERATION

The filter soot mass load has been calculated with an in-house developed mathematical model which takes into consideration the exhaust conditions, ΔP, filter geometry and soot microstructural properties



Step A: FE is high because the filter is loaded with soot

Step B: FE is decreased to 0.89 (fast regeneration-clean filter)

Step C: FE is decreased initially due temperature decrease. Then starts increasing again (from 0.87 to 0.92) with soot accumulation.

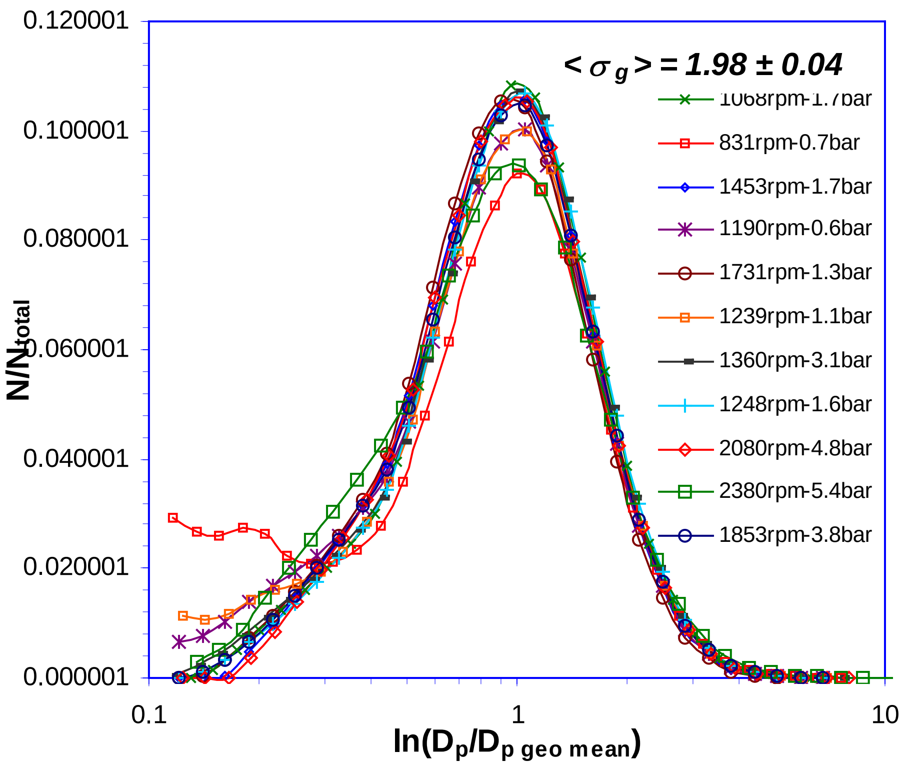
Step D: FE initially decreases due to temperature further decrease and then increases as soot accumulates in the filter. Noticeably, it remains constant after a short period at approximately 0.91 because at these conditions no further soot is stored into the filter (CRT® effect).

Step E: FE is increased to 0.97 because temperature is increased to 635 C

Step F: FE is again decreased due to temperature decrease.

Step G: FE is again increased to 0.97 (due to temperature increase) and then decreases as soot is oxidized

EEPS NEDC Size distribution in Harris-Maricq Coordinates



$$\sigma_g = \exp([\frac{1}{D_f(2b(D_f)+1)}\ln(4+2/q)]^{0.5})$$

Konstandopoulos and Kostoglou (2006)

On the σ_g of diesel particle size distributions

- 5 engines (1 Euro II, rest Euro III) with engine displacement 1.9-2.4 l
- 35 operating points 3 CR systems with different calibrations

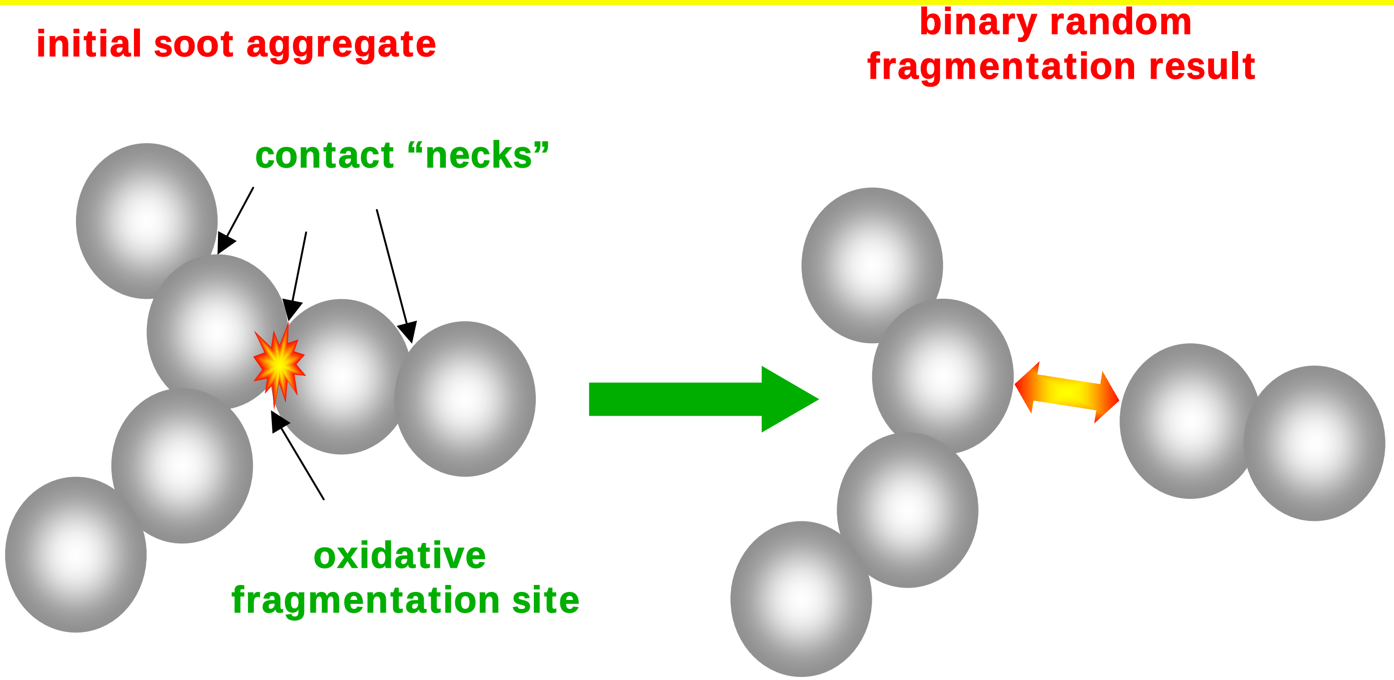
Fuel Injection System	σ_g	STD
Common Rail-1	1.88	± 0.09
Common Rail-2	1.94	± 0.09
Common Rail-3	1.86	± 0.15
Pump Unit Injector	1.90	± 0.14
Rotary Pump	1.85	± 0.04
Average	**1.89**	**± 0.08**

→ **D_f = 2.4**
For random binary fragmentation

Including Harris & Maricq's data
the average is 1.84 +/- 0.08 (ie 4%)

Konstandopoulos & Kostoglou (2003)

OXIDATIVE FRAGMENTATION



Continuous, binary random fragmentation process with size dependent rate:

$$S_i = Ai^{b(D_f)} = Ai^{aD_f^n} = Ai^{1/D_f}$$

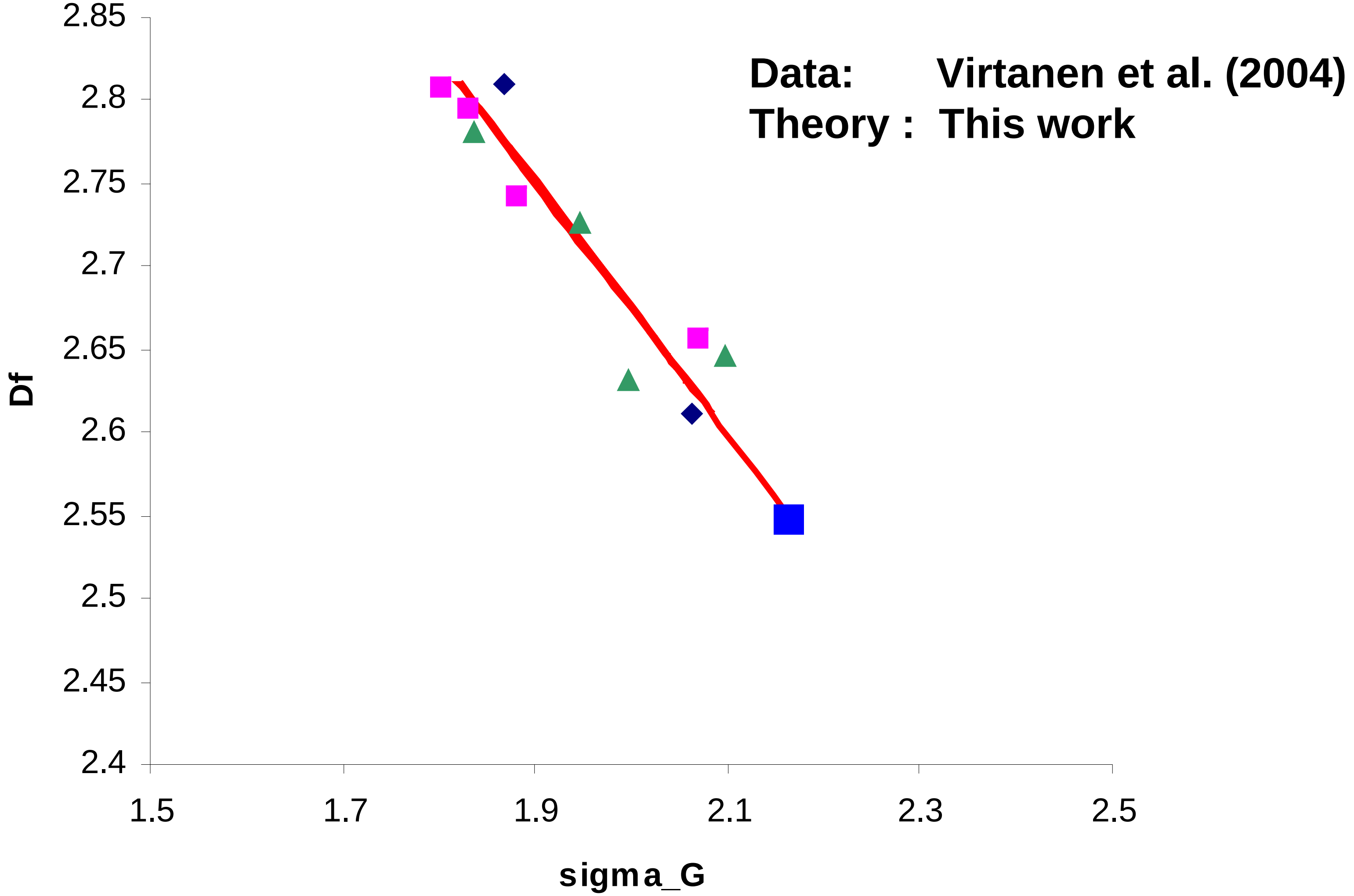
Fragmentation kernel

$$C_{i,j} = 2/(j-1)$$

Coagulation kernel (continuum)

$$B_{i,j} = B_o(i^{-1/D_f} + j^{-1/D_f})(i^{1/D_f} + j^{1/D_f})$$

Oxidative fragmentation population dynamics explains all available σ_g of diesel particle size distributions



CONCLUSIONS-1

- **Small but systematic differences were found between SMPS and EEPS size distributions under steady state conditions**
- **Total number concentration between SMPS, CPC and EEPS agrees to within 15% - 30 %. ELPI correlates with all instruments but measures lower total concentration.**
- **SMPS, CPC and ELPI correlate linearly with PAS and DC**
- **PAS/DC ratio decreases across a DOC in a temperature dependent fashion.**
- **CPC, ELPI and EEPS used during transient cycles to measure the filtration efficiency (on a number basis) of various DPF media do not always give the same result, with the CPC being the most noiseless and EEPS the most noisy.**

CONCLUSIONS-2

- CPC, ELPI and EEPS can pick reduced filtration efficiency events during the transient cycle due to high filtration velocities. These events are diminishing with soot load increase in the filter.
- In some higher porosity DPFs blow-off can be observed over the transient cycle, although not all instruments show it to the same extent.
- A methodology for measuring the filtration efficiency during regeneration as a function of soot load in the filter was developed.
- Our current work focuses on
  - ✓ Application of the oxidative-fragmentation population dynamics and the extraction of the evolution of the particle morphology during the transient cycle, as we have already reported in the past for steady state tests.
  - ✓ Extending our transient filtration models to describe mechanistically particle migration in the filter and blow-off

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- **Our APT Lab colleagues**