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SEA-EFFECTS BC 2015-2016

Tekes Arctic seas program

SEA-EFFECTS BC

Black carbon measurements from ship engine when using different marine fuels

ICCT's 3rd and final Workshop on Marine Black Carbon Emissions: BC Control Strategies

September 7-8, 2016, Vancouver, Canada

Research organisations

- VTT Technical Research Centre of Finland Ltd. (P. Aakko-Saksa, T. Murtonen, H. Vesala, P. Koponen, S. Nyyssönen, K. Lehtoranta, T. Pellikka, J. Lehtomäki),
- Finnish Meteorological Institute, FMI (H. Timonen, K. Teinilä, R. Hillamo)
- Tampere University of Technology,TUT (P. Karjalainen, N. Kuittinen, P. Simonen, T. Rönkkö, J. Keskinen)
- UTU (O-P. Brunila, E. Hämäläinen)

Industrial partners

- Funding from Wärtsilä Finland Oy, HaminaKotka Satama Oy, VG-Shipping Oy, Pegasor Oy, Spectral Engines Oy, Gasmet Technologies Oy, Vopak Oy and Kine Robot Solutions Oy
- Contribution in the experiments: Wärtsilä Finland Oy, VG-Shipping Oy, Pegasor Oy, Spectral Engines Oy and Gasmet Oy

External contributions

- AVL (Austria), Metropolia, UEF, Gasera Oy in the BC measurements

The authors would like to acknowledge financial support from Tekes (40356/14) and from industrial partners, Wärtsilä, Pegasor, Spectral Engines, Gasmet, VG-Shipping, HaminaKotka Satama Oy, Oiltanking Finland Oy and Kine Robotics,

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The SEA-EFFECTS BC project

With the expected rise in commercial shipping **in the Arctic, ship emissions are increasing**. Growing attention is given to **black carbon (BC), which increase global warming and ice melting through deposition to ice and snow**. IMO is evaluating needs for control of BC. SEA-EFFECTS BC aims at **more reliable and unequivocal basis of BC emission evaluation to shipping environment, and towards new options for on-line monitoring techniques**.

WP1	**Black carbon (BC) and on-line measurement techniques** **Laboratory tests in September 2015** Evaluation of current methods and update by using fuels with different sulphur contents and biodiesel.
WP2	**BC measurement validation on-board: September 2016** Validation of selected black carbon measurement methods on-board (ship equipped with scrubber)
WP3	**Impact of anticipated emission regulations on business potential**

CIMAC CONGRESS
HELSINKI | JUNE 6–10, 2016

2016 | 068

Black carbon measurements using different marine fuels

08 Basic Research & Advanced Engineering

Päivi Aakko-Saksa, VTT Technical Research Centre of Finland Ltd

Timo Murtonen, VTT Technical Research Centre of Finland Ltd., Hannu Vesala, VTT Technical Research Centre of Finland, Päivi Koponen, VTT Technical Research Centre of Finland, Sami Nyyssönen, VTT Technical Research Centre of Finland Ltd., Harri Puustinen, VTT Technical Research Centre of Finland Ltd, Kati Lehtoranta, VTT Technical Research Centre of Finland Ltd., Hilkka Timonen, Finnish Meteorological Institute, Kimmo Teinilä, Finnish Meteorological Institute, Risto Hillamo, Finnish Meteorological Institute, Panu Karjalainen, Tampere University of Technology, Niina Kuittinen, Tampere University of Technology, Pauli Simonen, Tampere University of Technology, Topi Rönkkö, Tampere University of Technology, Jorma Keskinen, Tampere University of Technology, Erkka Saukko, Pso, Monica Tutuianu, AVL List GmbH, Roman Fischerleitner, AVL List GmbH, Liisa Pirjola, Helsinki Metropolia University of Applied Sciences, Olli-Pekka Brunila, University of Turku, Esa Hämäläinen, University of Turku

CIMAC Paper is available at: http://www.cimac.com/publication-press/technical-database/index.html

Research Gate: https://www.researchgate.net/home

Test matrix

Wärtsilä Vasa 4R32 LN 1.6 MW medium-speed engine at VTT's engine laboratory.

Two engine loads:

- 75% corresponding to the open sea engine loading conditions
- 25% corresponding to the near-harbor engine loading conditions.

Test fuels:

- Marine Diesel Oil with 0.1% sulphur content: "0.1%S"
- Fuel with 0.5% sulphur content: "0.5%S" (not a distillate)
- Heavy fuel oil: "2.5%S"
- A blend of "biofuel" and distillate in ratio of 30:70: "Bio30"

Engine oil: Shell Argina XL 40 engine oil.

Engine and fuels

Wärtsilä Vasa 4R32 LN E	
Nominal power, kW	1640
Number of cylinders	4
Speed, rpm	750
Bore/stroke, mm	320/350
Compression ratio	13.8
Rotating direction	clockwise
Firing order	1-3-4-2
Exhaust valve opens / closes	56 °bbdc / 44 °atdc
Inlet valve opens / closes	52 °btdc / 28 °abdc
Injection nozzle opening pressure	520 bar
Static injection advance	12.3 deg

	0.1%S DMB	0.5%S IFO	2.5%S HFO	Bio30
Density (15/50 °C), kg/m^3	870/-	-/906	-/979	866/-
Viscosity (40/50 °C), mm^2/s	4.8/-	-/127	-	6.7/-
Viscosity (80 °C) mm^2/s	-	-	187	-
Carbon residue				
10 %D, % (m/m)	<0.1	-	-	2.4
100 %, % (m/m)	-	3,7	18,3	-
Hydrogen sulfide, mg/kg	<10	<10	<10	<10
Water (K.-F.), mg/kg	53	-	-	197
Water, % (V/V)	-	0.22	0.54	-
Total sediment, % (m/m)	<0.01	0.25	0.37	<0.01
Ash (775 °C) , % (m/m)	<0.005	0.038	0.094	<0.005
Flash point, °C	86.5	206.0	103.0	67.5
Pour point, °C	0	+30	-5	-9
Cloud point, °C	+3	-	-	-3
90 % (V/V) recovery, °C	358	-	-	334
Cetane Index/Number	49.9/-	-/44.5	-/26.1	46.4/-
CCAI	-	780	848	-
Acid number (TAN), mg KOH/g	0.025	0.619	0.776	3.33
Strong acid number, mg KOH/g	-	-	<0.1	<0.1
HFRR (lubricity), µm	349	178	154	220
Copper strip corrosion	1	1	1	1
Steel corrosion	1	1	intensi-ve rust	1
Iodine value g I/100g	-	-	-	49
Heating value, lower kJ/kg	42.5	42.1	40.3	40.7

BC measurements

From the IMO's candidate methods, FSN, PAS and MAAP were covered.

Smoke Meters. BC based on Filter Smoke Number (FSN). The relative change in optical reflectance of visible light from a filter.	AVL 415S *(VTT)* AVL 415SE *(AVL)*
AVL Micro Soot Sensor, photo acoustic method (PAS).	AVL MSS (AVL)
Multiangle Absorption Photometer (MAAP). Relative change in optical transmission as particles are collected and measurement of reflectance of scattered light with multiple detectors.	MAAP 5012 *(FMI)*
Aethalometers. Change in absorption of transmitted light due to continuous collection of aerosol deposit on filter.	MAGEE AE42 *(FMI)* MAGEE AE33 *(Metropolia)*
EC/OC thermal-optical analysis. Organic and elemental carbon, in-stack (EN 13284-1) and partial flow dilution (ISO 8178) samples.	Sunset 4L *(VTT)*
The Soot Particle Aerosol Mass Spectrometer, SP-AMS. Quantitative aerosol mass loadings, BC and metal analysis.	SP-AMS (FMI)

Sample treatment and other analyses

Engine testing, gaseous emissions, PM with in-stack (EN 13284-1) and partial flow dilution (ISO 8178) sampling	VTT
PM compositional analyses incl. soluble organic fraction, anions, elements and PAHs	VTT and subcontractors
Dilution system for MAAP, AEs, SP-AMS and TUT instruments.	TUT
Sample treatment with catalytic strippers (CS) and thermodenuder (TD)	Pegasor, TUT
Pegasor Particle Sensor (PPS). Measurement of electrical charge carried by particles.	Pegasor
In-depth analysis, e.g. PAM, SMPS, CPC, ELPI+, TUT-HTDMA	TUT, FMI

BC instruments – parameters

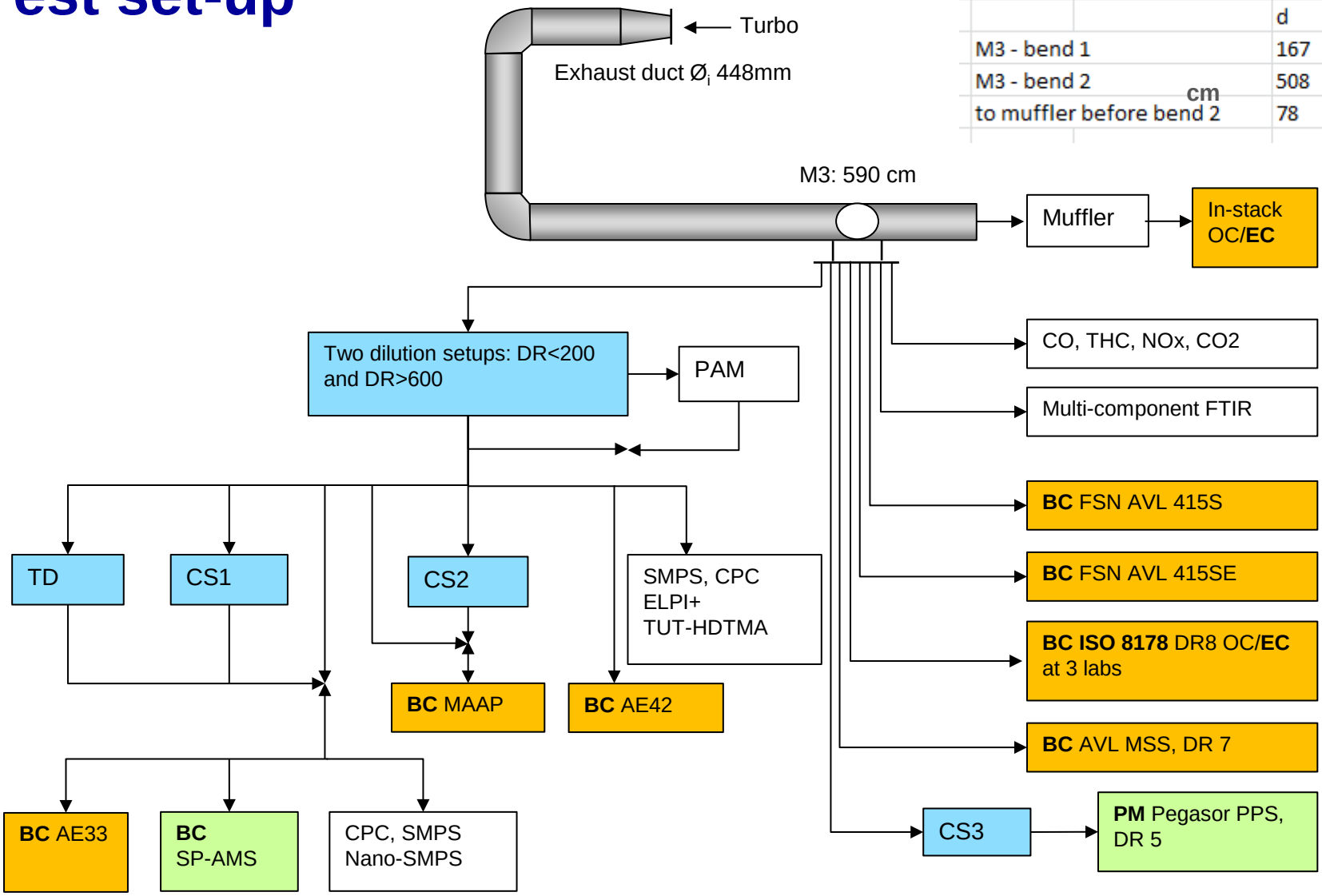
	Dilution ratio	Sample	Range (diluted exhaust)	Detection limit	Time-base
AVL 415S/SE	No dilution	~10 lpm	BC 0-32000 mg/m^3	~0.02 mg/m^3	
AVL MSS	DR 7 (spec 2-20)	3.8 lpm	BC 1-1000 mg/m^3		up to 10Hz
MAAP	DR <200; DR >600	6 lpm (spec 16.7 lpm), PM1	BC 0-60, 0-180 µg/m^3 (30/10 min 16.7 lpn)	<0.1 µg/m^3 (2 min.)	1 min
Aethalo-meters	DR <200; DR >600	2 lpm. 1 min av. (spec 2-5 lpm) PM1	BC <0.01 to >100 µg/m^3	<0.005 µg/m^3 (1 hour)	1 min (1 s option)
SP-AMS	DR <200; DR >600	0.1 lpm	BC 0.04 µg - 2 mg/m^3	<0.04 µg/ m^3 (1 min)	1 min
PPS-M	DR 5	<10 lpm	PM 1–250 mg/m^3		0.2 s
EC	[a]		EC range 1-15 µgC/cm2 [b]	EC 0.2 µgC/cm2	

[a] ISO 8178 PM sampling: DR 8, in-stack sampling: no dilution
[b] Samples in this study: EC 0.7-16 µgC/cm2.

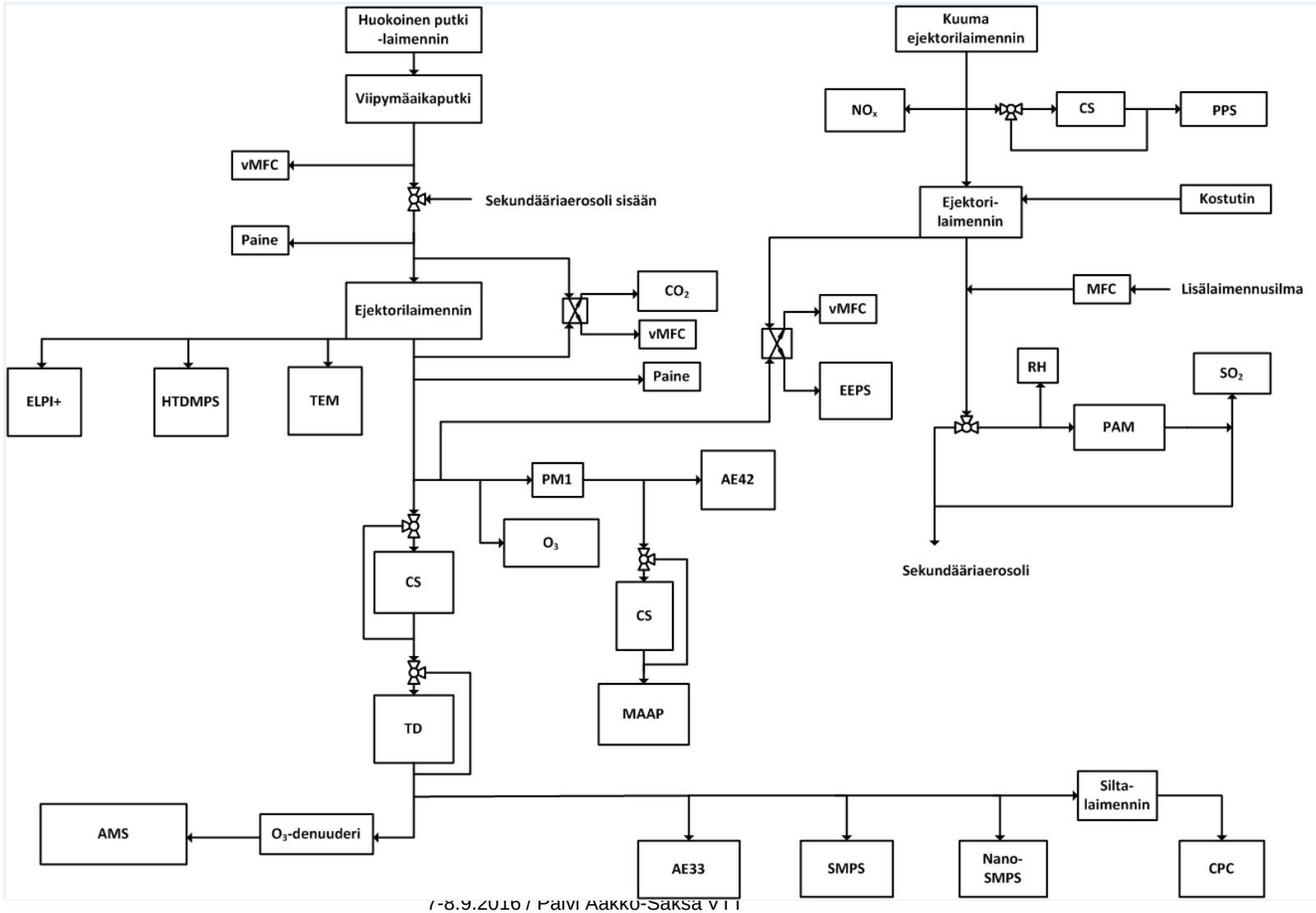
Test set-up

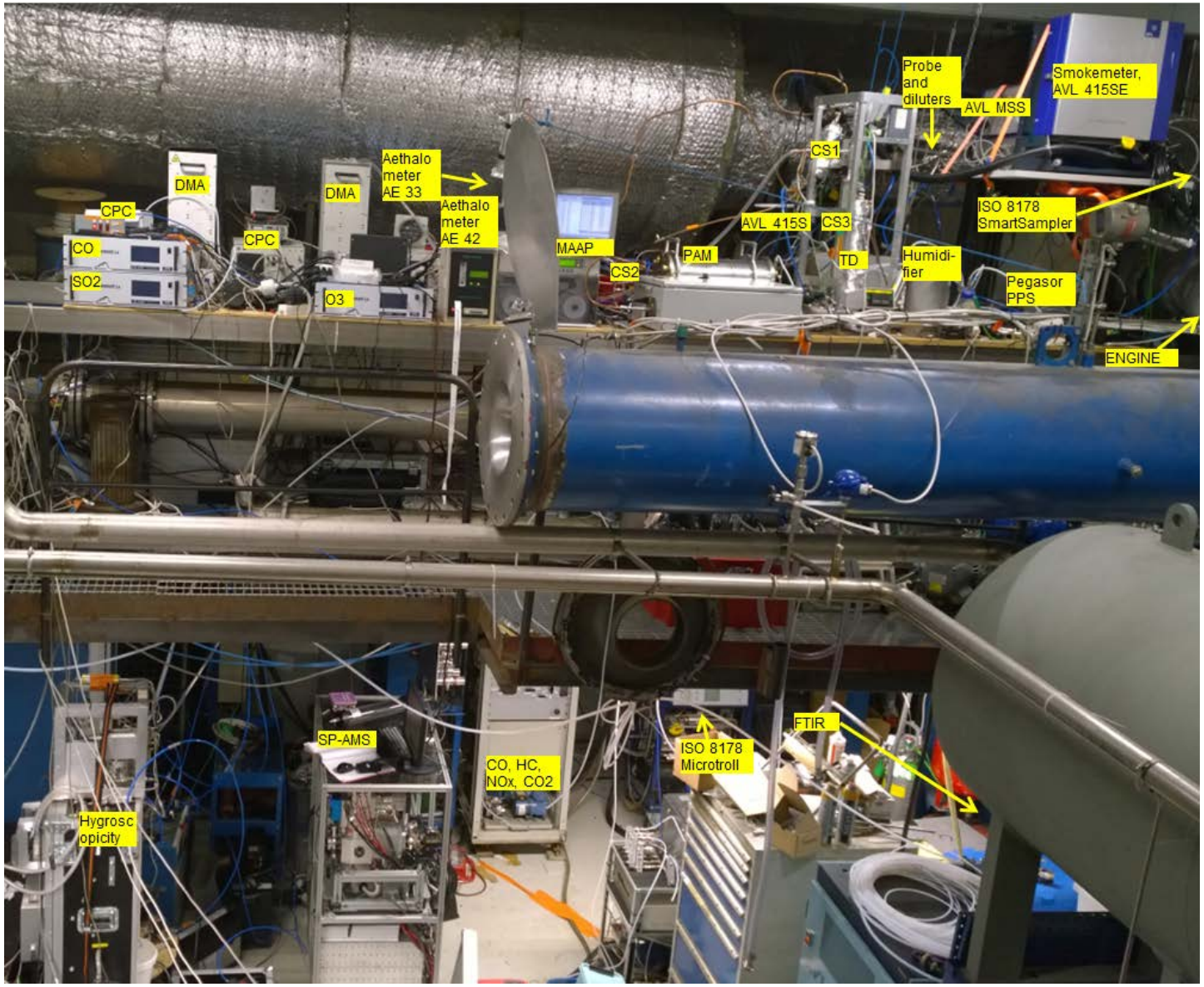
	d	d/id
M3 - bend 1	167	3,8
M3 - bend 2	508	11,4
to muffler before bend 2	78	1,8

cm



TUT dilution system




Probe and diluters
Smokemeter, AVL 415SE
AVL MSS
CS1
Aethalo meter AE 33
DMA
DMA
CPC
CPC
Aethalo meter AE 42
ISO 8178 SmartSampler
AVL 415S
CS3
MAAP
PAM
TD
Humidi-fier
CS2
CO
SO2
O3
Pegasor PPS
ENGINE
SP-AMS
CO, HC, NOx, CO2
ISO 8178 Microtroll
FTIR
Hygrosc opicity

Daily protocol

Warm-up	**10 minutes at 50% load** **50 minutes at 75% load.**

Tests at 75% load (morning session)	• **In-stack:** in minimum three collections, Munktel MK360 quartz filters
	• **ISO 8178 collections**
	  o Pallflex TX40 filters (primary and back-up): 7-8 collections with 2 sampling systems
	  o Munktel MK360 quartz filters and Pallflex TX40 back-up filters: min. 3 collections
	• **FSN AVL 415S/SE and AVL MSS** sampling periods synchronized with ISO 8178 Microtroll
	• **Real-time instruments** measuring continuously
	• **Periodically ON/OFF**: CS1&TD before AE33 and SP-AMS. CS2 before MAAP. CS3 before PPS.

Load change	**Stabilisation at least 30 minutes**
Tests at 25% load	Same procedure as at 75% load

The best practises for engine emission tests followed

Before/after test campaign

- **Engine and test set-up stabilisation** before the campaign
- **Lube oil running hours** checked
- **Fuel and lube samples** analysed
- **One fuel tested before and after campaign** (stability of the set-up)

During the test campaign

- **Warm-up and load change protocol**
- On-line measurements (e.g. NO with FTIR) to **follow engine stability**
- **Fuel temperature** adjusted according to engine manufacturer's requirements

Periodical recordings

- Engine speed, alternator power, rack position, bearing temp, HC of blow-by
- Test cell T&RH, intake air T, pressure diff, under pressure in meas pipe, T and P before/after TC, TC speed, air gauge P before cooler/ in receiver, air T in receiver, exhaust T, cyl. T
- Water T from different locations
- Fuel mass flow rate in/out/booster, fuel T/P after feed pump, fuel P before/after engine (booster), fuel volume flow rate in/out, fuel T before/after engine, fuel viscosity before engine, fuel P on engine (in/out)
- Lub. oil T from different locations, lube oil pressure

High dilution ratios needed for some BC instruments are a source of uncertainty

BC instruments designed for the atmospheric measurements, such as MAAP and aethalometers, require high dilution ratios at high BC concentrations.

Dilution ratio is a multiplier in the calculation of the BC results, and thus uncertainty in DR is directly reflected in the uncertainty of the BC result.

When using high DR and/or pre-treatment (CS, TD), size-dependent corrections for **soot particle losses are need** for the calculation of the results.

$$DR = \frac{C_{raw} - C_{bg}}{C_{dil} - C_{bg}}$$

High dilution ratios are challenging. How to measure accurately DR >500?

In these measurements

- DR based on CO_2 measurements*) at different locations of the sampling system.
- Water content of exhaust for dry/wet correction (Gasmet FTIR).
- Sampling and dilution air T, RH, impurities (PN) adjusted/monitored.
- Heated ejector diluter (350 °C).

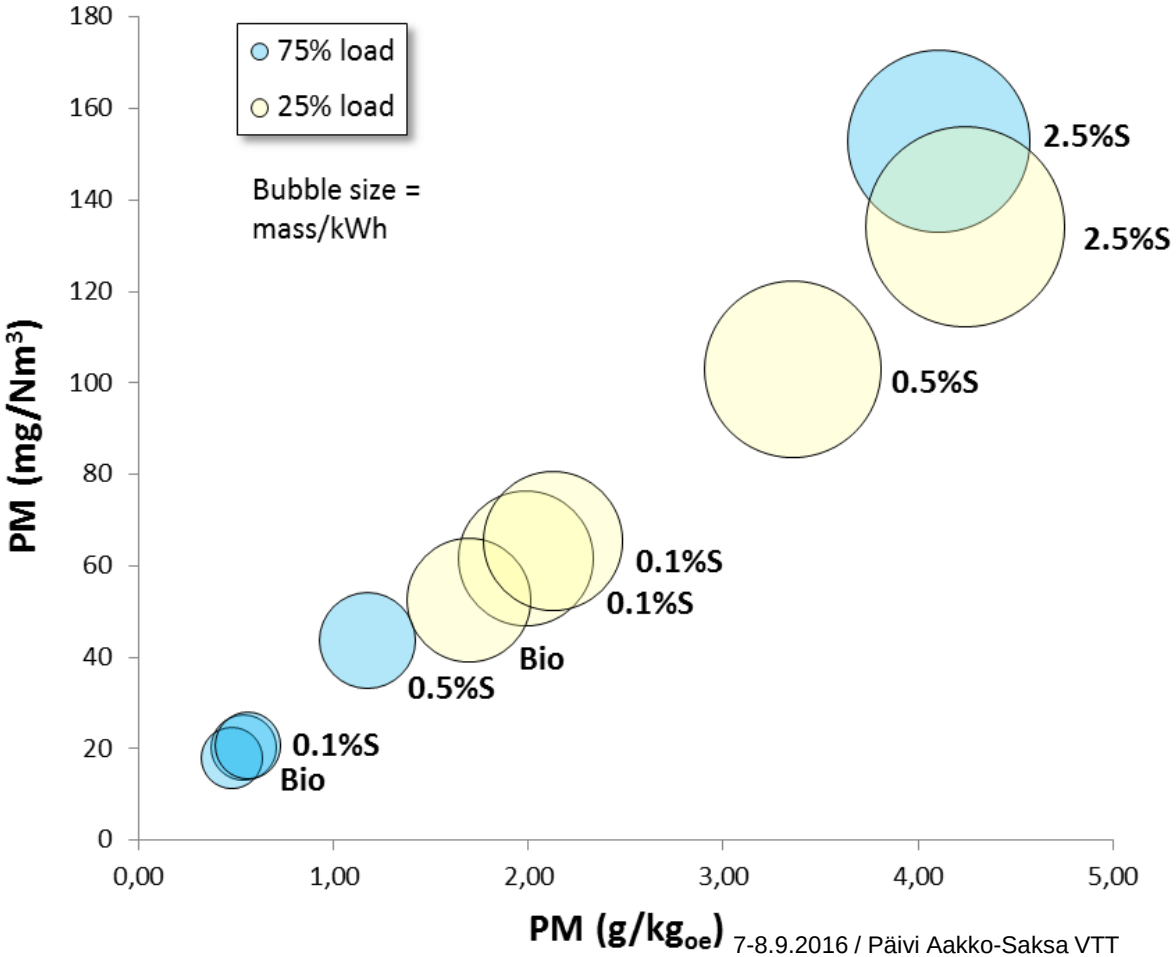
Observations

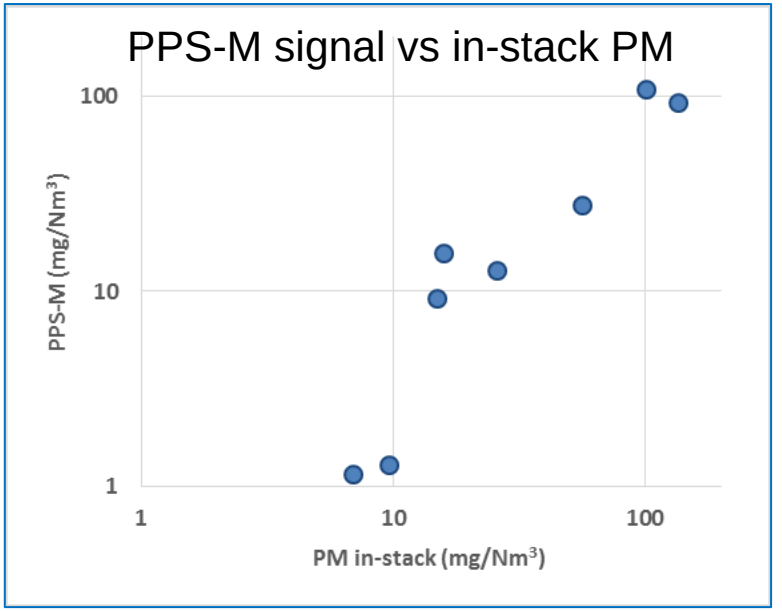
- When using dried only dilution air, accurate on-line analysis of CO_2 of dilution air is needed due to CO_2 contamination risk in the engine environment.
- **Using ultra-pure dilution air without CO_2 is recommended.**

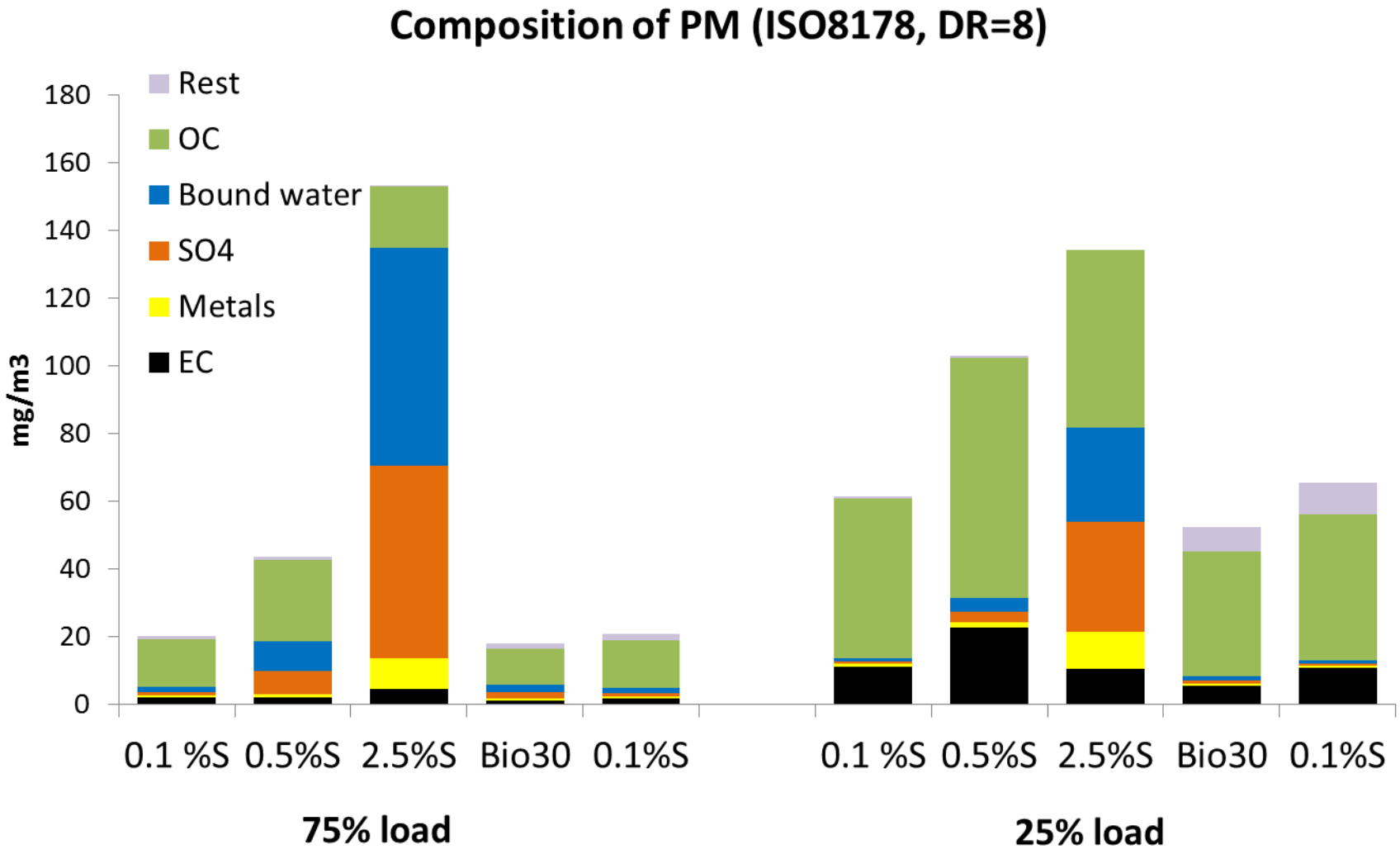
*) NO_x is not feasible for determination of DR due to low diluted NO_x concentration (e.g. at . NO_x of 1000 ppm and DR 500 → diluted NO_x 2 ppm)

RESULTS FROM LABORATORY TESTS

Particulate matter PM (ISO 8178, DR8) as mass/Nm^3, kilograms of oil equivalent (kg_{oe}) and mass/kWh

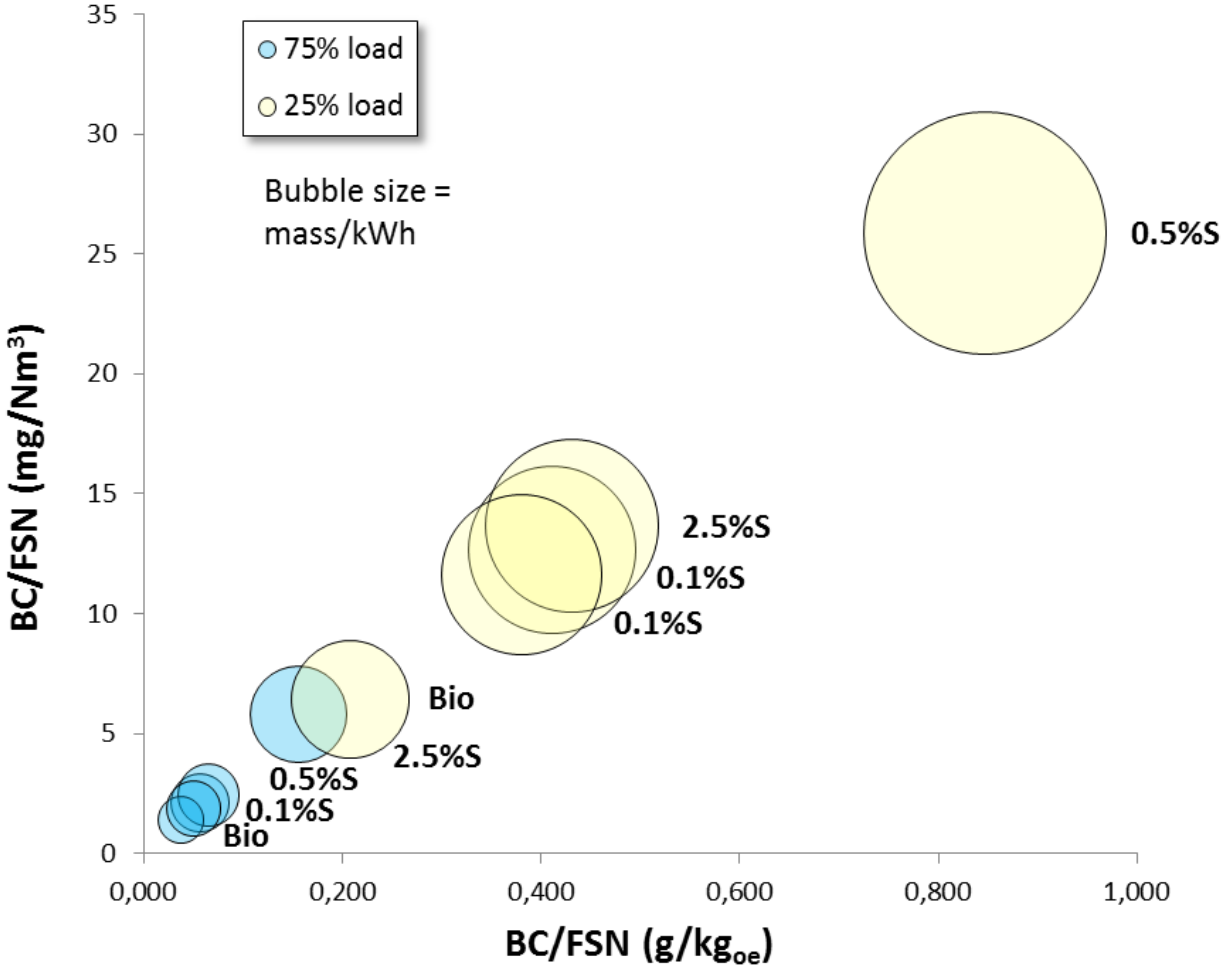


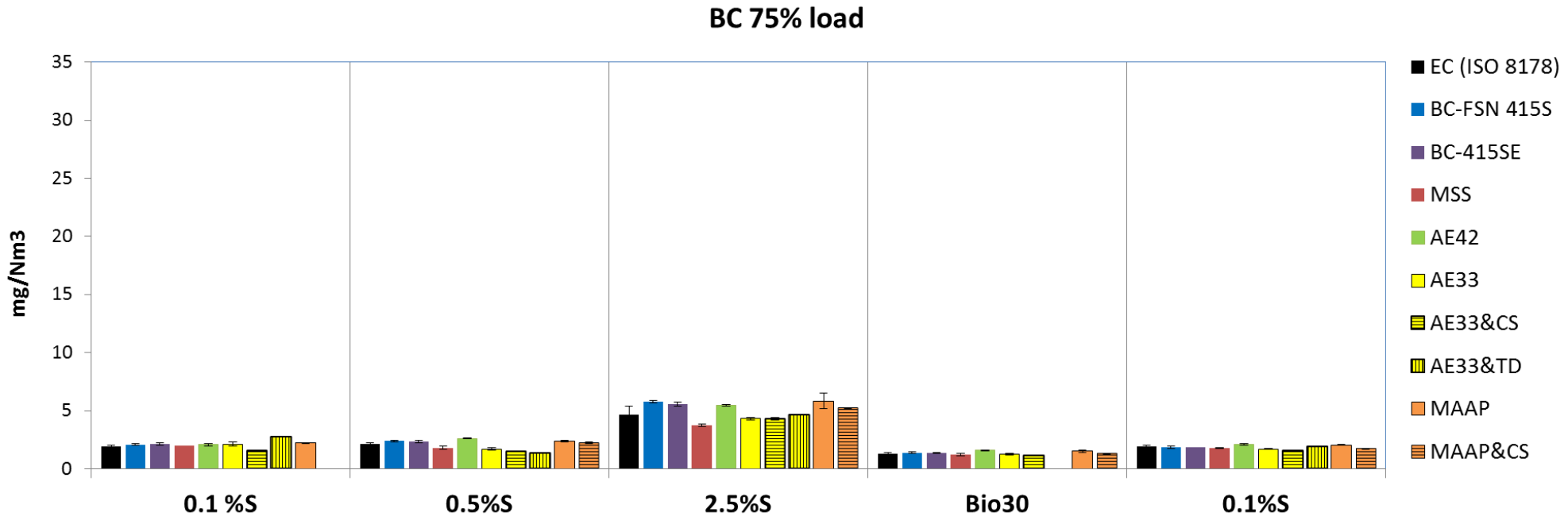


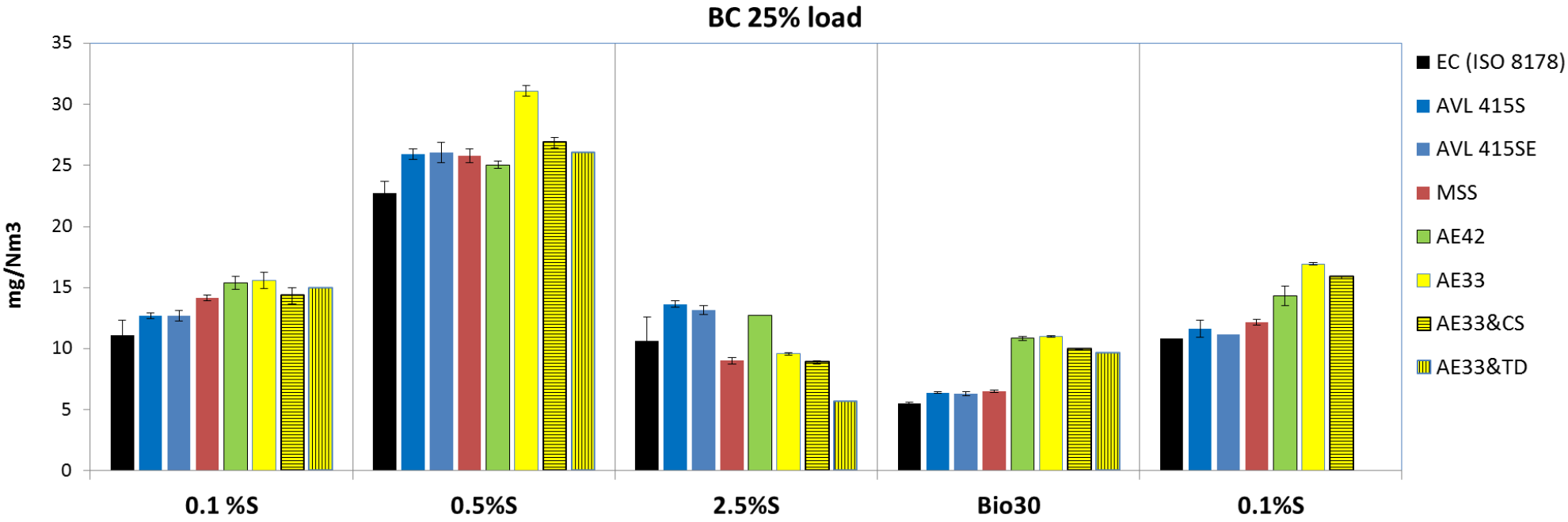


Share of EC in PM low for all fuels. Heavy PAHs lowest for 0.1%S and Bio30.

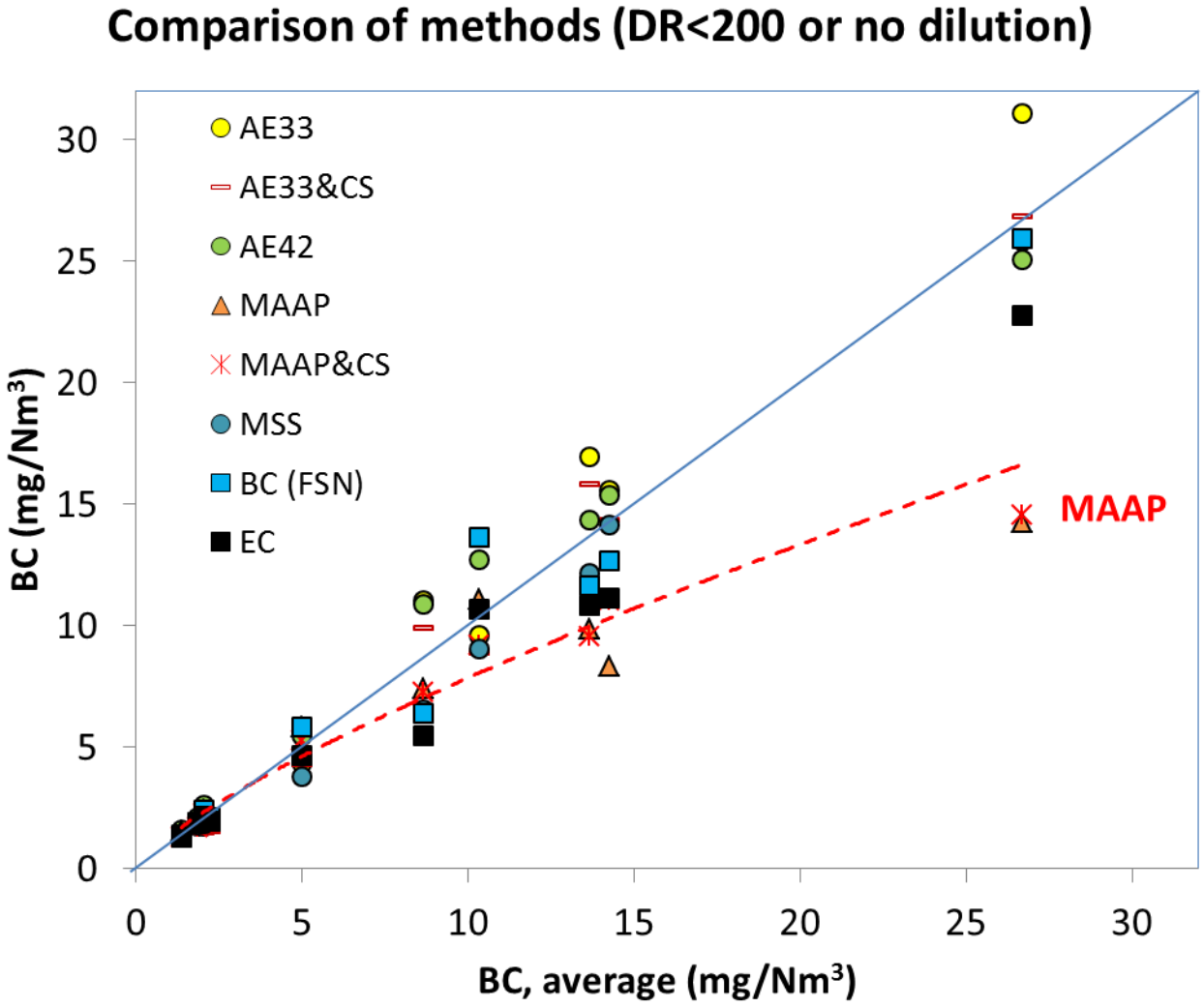
Black carbon emission in different units



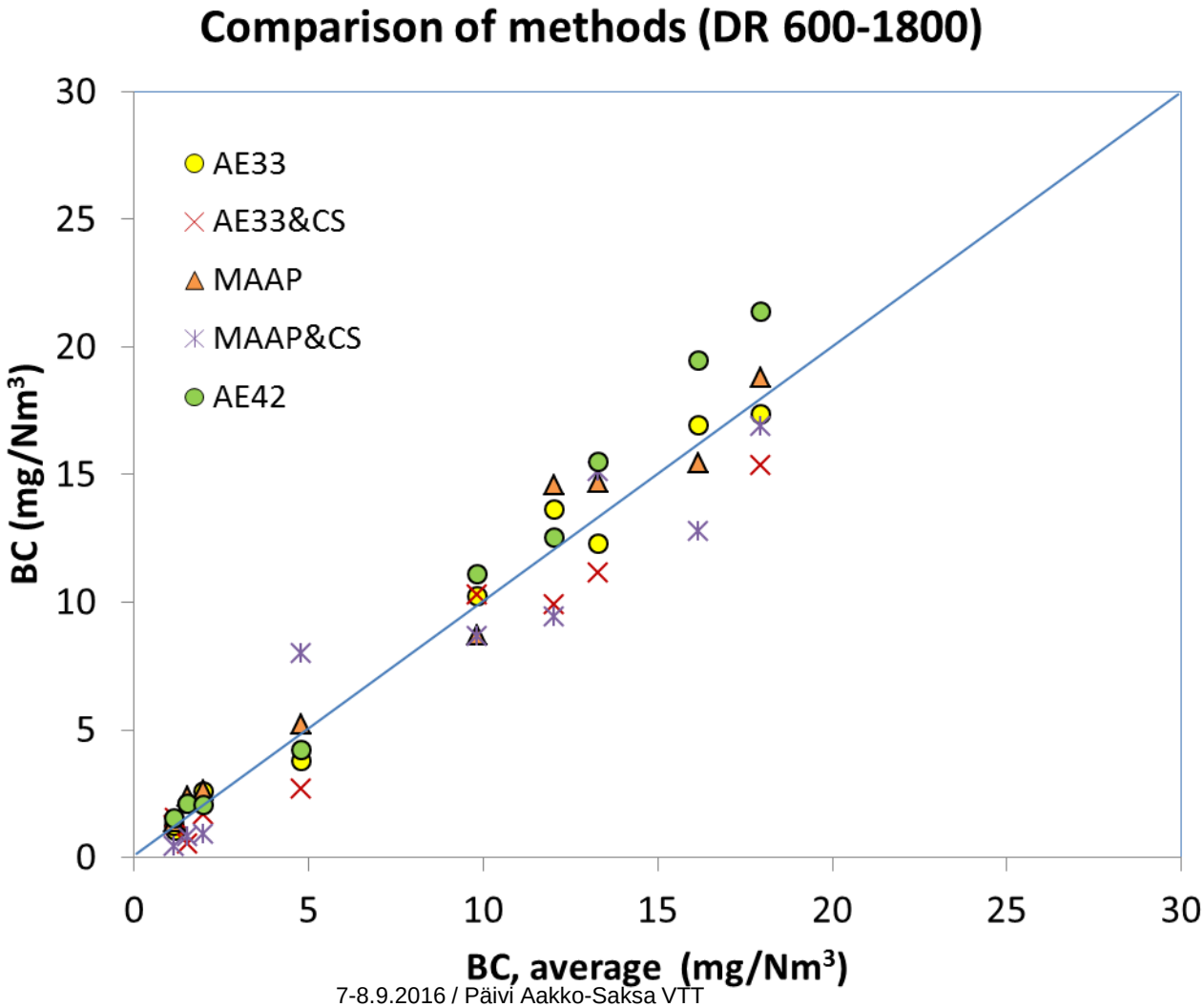

BC 75% load
mg/Nm3
35
30
25
20
15
10
5
0
0.1 %S
0.5%S
2.5%S
Bio30
0.1%S
EC (ISO 8178)
BC-FSN 415S
BC-415SE
MSS
AE42
AE33
AE33&CS
AE33&TD
MAAP
MAAP&CS


BC 25% load
mg/Nm3
35
30
25
20
15
10
5
0
0.1 %S
0.5%S
2.5%S
Bio30
0.1%S
EC (ISO 8178)
AVL 415S
AVL 415SE
MSS
AE42
AE33
AE33&CS
AE33&TD

Low BC with MAAP at high BC conc. when DR<200



…but similar BC level with MAAP and AEs at DR>500.



Note: BC results at DR>500 are not quantitative due to uncer-tainty in DR.

Hyvärinen et al. (2013) also observed a measurement artifact in the MAAP at high BC concentrations

averaging procedure of the photodetector raw signals. It was found that, in addition to the erroneous temporal response of the data, concentrations higher than 9 $\mu g\,m^{-3}$ (at the flow rate of 16.7 $L\,min^{-1}$) are underestimated by the MAAP. The underestimation increases with increasing BC accumulation rate. At a flow rate of 16.7 $L\,min^{-1}$ and concentration of about 24 $\mu g\,m^{-3}$ (BC accumulation rate $\sim 0.4\,\mu g\,min^{-1}$), the underestimation is about 30 %. There are two ways of overcoming the MAAP artifact. One method is by logging the raw

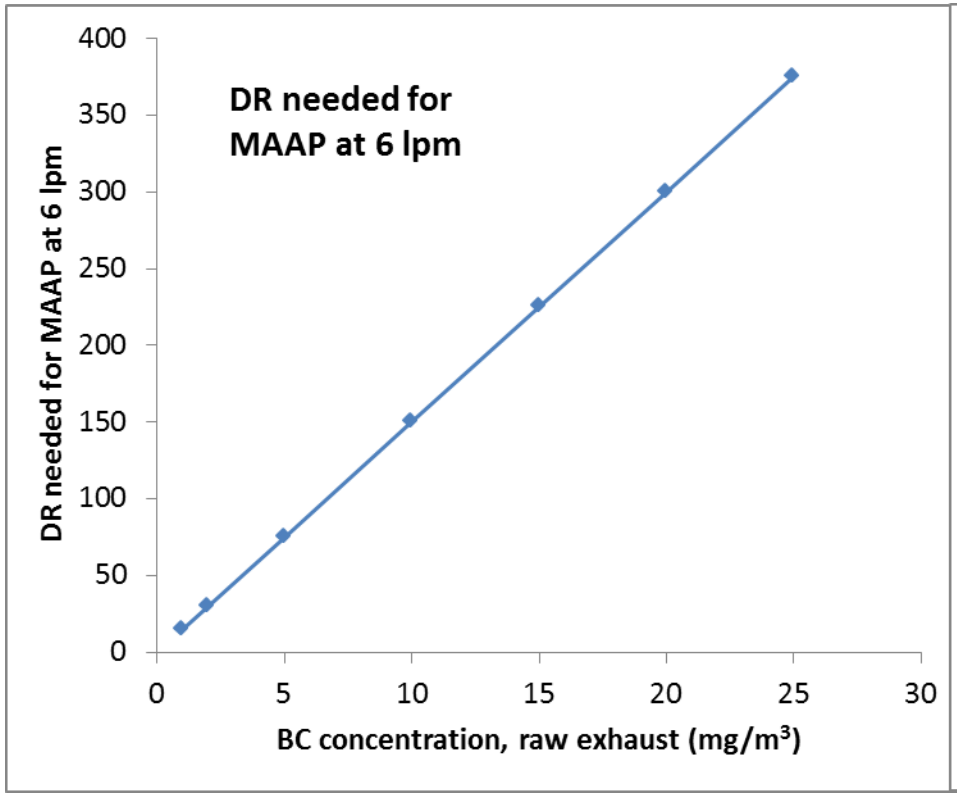
Atmos. Meas. Tech., 6, 81–90, 2013
www.atmos-meas-tech.net/6/81/2013/
doi:10.5194/amt-6-81-2013

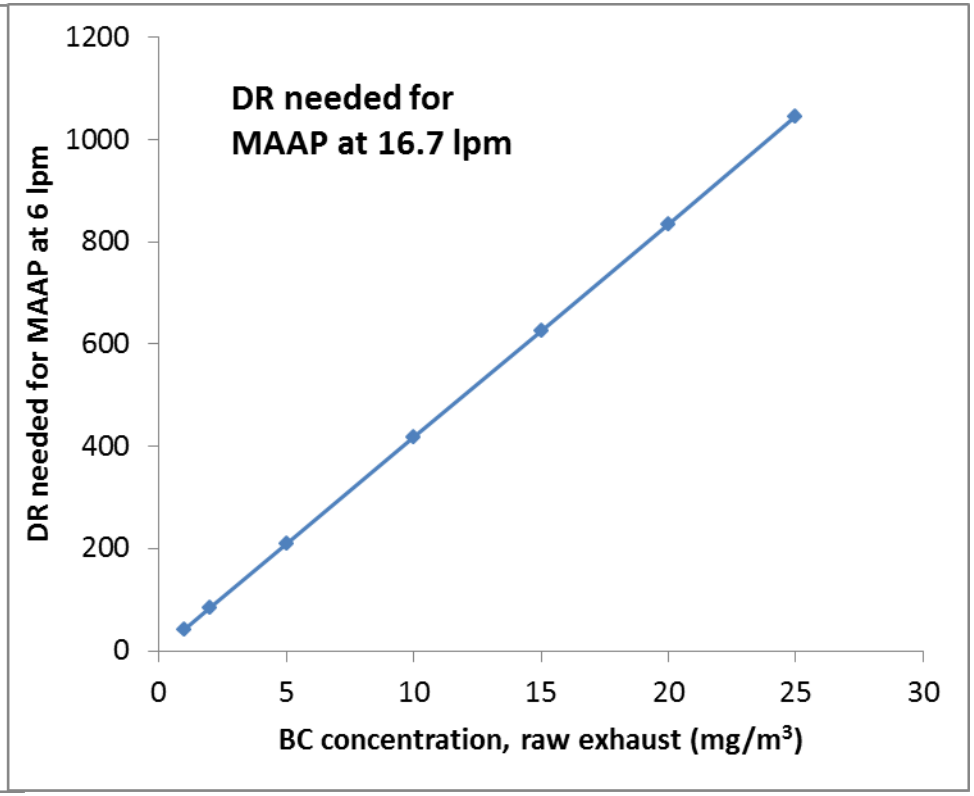
Correction for a measurement artifact of the Multi-Angle Absorption Photometer (MAAP) at high black carbon mas concentration levels

A.-P. Hyvärinen[1], V. Vakkari[2], L. Laakso[1,3], R. K. Hooda[1,4], V. P. Sharma[4], T. S. Panwar[4,5], J. P. Beu P. G. van Zyl[3], M. Josipovic[3], R. M. Garland[6,7], M. O. Andreae[6], U. Pöschl[6], and A. Petzold[8]

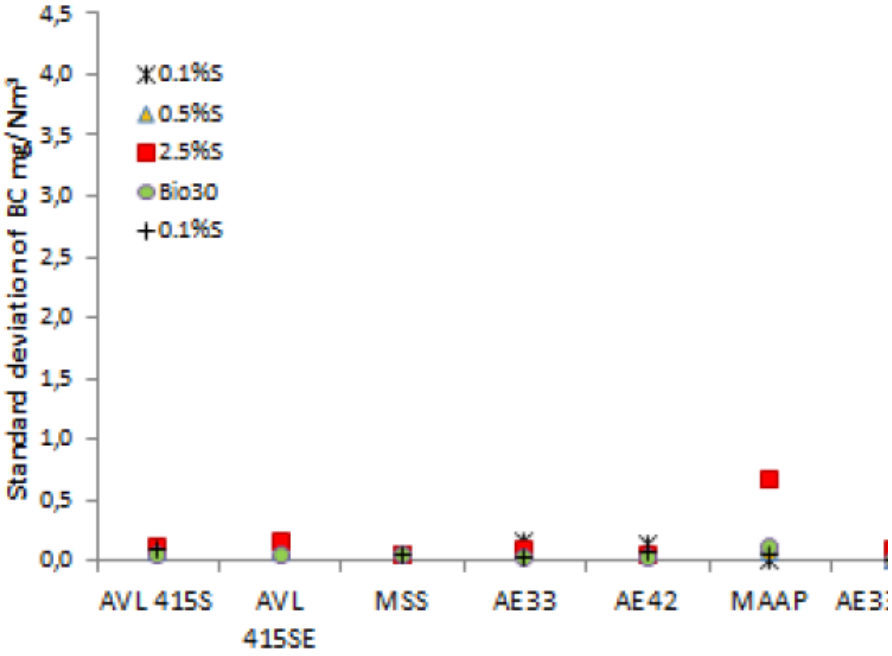
In Hyvärinen et al. MAAP underestimated BC by 30 % when mass accumulation rate exceeded 0.4 µg min^{-1}, which is equivalent to BC concentration of 24 µg m^{-3} at flow rate of 16.7 lpm (1 $m^3\,h^{-1}$). In our tests, MAAP flow rate was 6 lpm -> BC mass accumulation rate of 0.4 µg min^{-1} was reached at BC concentration of ***67 µg m^{-3}, which was exceeded with 0.1%S and 0.5%S fuels at 25% engine load using DR<200.***

Minimum DRs needed for MAAP

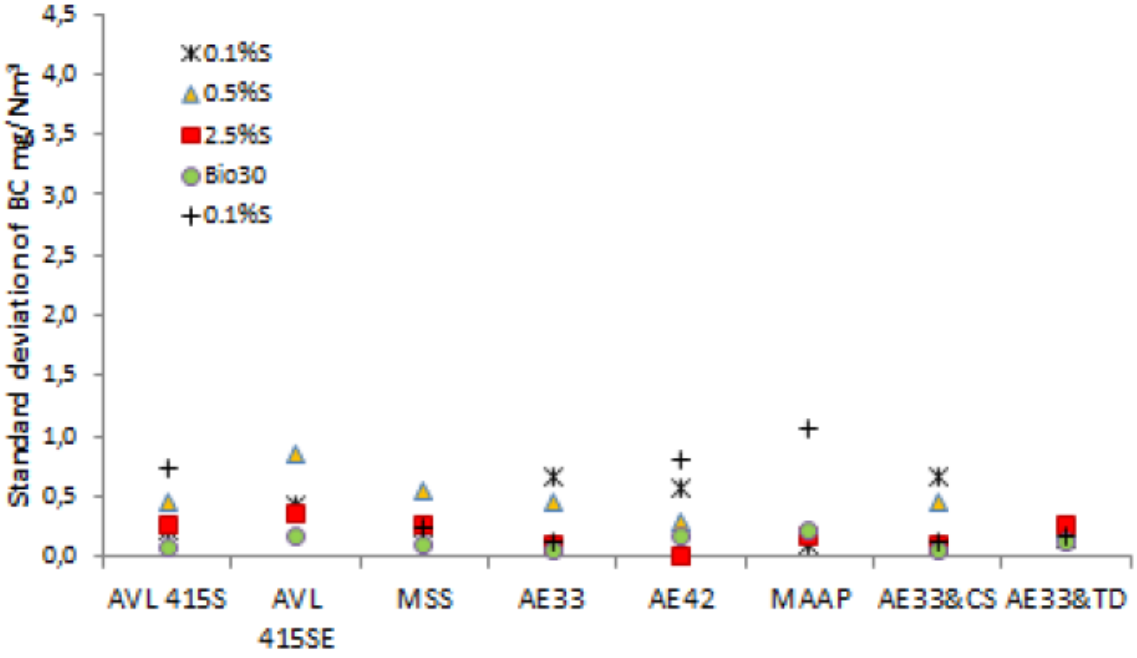




Standard deviation at 75% load



Standard deviation at 25% load



Findings on the BC measurement methods

Comparability was relatively good between the BC results obtained with two smoke meters, AVL MSS (PAS), aethalometers and MAAP. EC compared relatively well with BC.

High DRs required for MAAP and AEs at high BC concentrations lead to high uncertainty in the BC results (DR is a multiplier in calculation). For high DRs, ultra-pure dilution air w/o CO_2 is needed.

Measurement range of MAAP is particularly narrow. MAAP artifact can occur already at the BC concentration of 10 µg/m^3.

Many challenges can be alleviated, if instruments can operate without dilution or at low DR.

CS and TD might alleviate bias between different BC instruments, but at the cost of **increased complexity of the test set-up**.

When using high DR and/or pre-treatment (CS, TD), size-dependent corrections for soot particle losses are need for the calculation of the results.

With **high-sulphur fuels, clogging and corrosion** related problems are threats.

Findings on the BC control

The BC emission was dependent on engine load. **The BC emission was substantially higher at 25% load than at 75% load.**

75% load:

- The highest BC emission for the 2.5%S fuel, while the BC emission from the 0.5%S, 0.1%S and Bio30 fuels were lower.
- At the high load combustion temperature is high and combustion more complete even with asphaltenic fuels than at lower loads.

25% load:

- The highest BC emission for the 0.5%S fuel. Presence of BC precursors in fuel depends on crude oil and processing technology.
- The 2.5%S fuel, showed lower BC emissions than the 0.5%S fuel presumably as some metal oxides catalytically enhance combustion.
- The BC emissions for the 0.1%S and Bio30 fuels were also lower than those for the 0.5%S fuel.
- The lowest BC emission was observed for the Bio30 fuel presumably basing on its oxygen content.

Summary

Different instruments rated the BC emissions in the same order despite of their different measurement principles. **Challenges with high dilution ratios** needed for the BC instruments designed for the atmospheric measurements (MAAP, AEs) can be alleviated, if instruments can operate without dilution or at low DR.

The results unveiled dependences between the BC emissions, fuels and loads for the engine studied, and how different BC measurement methods reflected changes in BC emissions. For example, reduced sulphur content of the fuel efficiently reduced the PM emission, but not necessarily the BC emission. **BC was not directly dependent on the fuel sulphur content**.

Measurements continue on-board a ship equipped with scrubber in September 2016.


WHO'S
nvironnement S.A