Black Carbon Emission of Marine Diesel Engines

4th ICCT Workshop on
Black Carbon
Peter Lauer, 4 – 5 October 2017

Agenda

Motivation

Comprehensive characterization of particulate matter (PM) from marine medium speed 4-stroke diesel engines

Fuel influence & in service operation with focus on

- **Identical engine type**
- **PM emission & composition**
- **Elemental Carbon (EC)**

Comparison of measurement methods

- **FSN**
- **PAS**

Measurement methods not considered anymore (challenges already reported elsewhere)

- **LII**
- **MAAP**

Methods

With focus on EC or BC fraction of PM

PM measurement by MAN Diesel & Turbo (MDT) on filter samples according to

- **ISO-8178**

Subsequent analysis of PM filter samples for EC & OC with methods by

- **DNV-GL**
- **MDT**

Determination of equivalent Black Carbon (eBC) with

- **Filter Smoke Number (FSN) by MDT**
- **Photoacoustic Sensor (PAS) by MDT**

Analysis of fuels performed by

- **ASG Analytik-Service Gesellschaft mbH, 86356 Neusäss, Germany**
- **MDT**

Methods

PM according ISO-8178 vs. FSN according ISO-10054 vs. Photo Acoustic Soot Sensor

AVL 472 Smart Sampler Modular GEM140 (special mobile version)

Based on ISO-8178 PM @ 47±5°C after dilution on Quartz (Pall QAO 2500) or Teflon (Pall Emfab TX40HI20) fiber filters

Remark:
Particulate measuring according to ISO-8178 is conclusively proven to be effective for fuel sulfur levels up to 0.8% only

AVL 415-SE Smoke Meter

Based on ISO-10054 absorption with highest sensitivity @ 550-600 nm wavelength, light scattering is of no influence due to reflection of scattered light from white reflection plate identical to clean filter

Remark:
Operates on undiluted exhaust gas according to ISO-10054

AVL 483 MSS^{plus} Micro Soot Sensor

Based on photoacoustic principle & measured by microphone, wavelength adjusted to minimize cross-sensitivity (NO_x), sound pressure resonance chamber influenced by temperature, pressure & humidity

Remark:
Operates on diluted exhaust gas, incorporates a thermophoretic loss compensation

Methods

EC / OC analyzing methods

Coulometric EC method from PM filter samples:

VDI-2465-1:	**filter-split, ½ filter: Thermodesorption of TC @ 650°C in O_2 ½ filter: Toluene-Propanol extraction & thermodesorption of OC @ 500°C in N_2, subsequent thermodesorption of EC @ 650°C in O_2**
VDI-2465-2:	**Thermodesorption of OC @ 80-620°C in He, subsequent thermodesorption of EC @ 300-700°C in O_2**
DNV-GL in-house:	**Improved VDI-2465-2 after extraction VDI-2465-1 & thermodesorption of OC @ 700°C in He & subsequent EC @ 850°C, see [IMO PPR 1/8/4]**

For reliable EC determination, charring effects must be excluded!

Optical eBC method:

AVL-415 /-S/-SE: **Filter Smoke Number (FSN) is reported @ 25 °C & 1000 mbar**

Correlation formulas used for calculation of eBC mass concentration

heated: $eBC\ [mg/m^3] = 1 / 0.405 \times 5.32 \times FSN \times e^{0.3062 \times FSN}$

unheated: $eBC\ [mg/m^3] = 1 / 0.405 \times 4.95 \times FSN \times e^{0.38 \times FSN}$

Photoacoustic eBC (PAS) method:

AVL-483 MSS^{plus}: **Micro Soot Sensor**

Methods

Fuel properties

Fuel	Heavy Fuel Oil (HFO)	Marine Diesel Oil (MDO)	Marine Diesel Oil (MDO)	Marine Gas Oil (MGO)	EN-590 Gas Oil (ULSD)	Marine Diesel Oil (MDO)
	ship	ship	test bed	test bed	test bed	test bed
Category	Residual	Distillate	Distillate	Distillate	Distillate	Distillate
Type	RM 180	DM-B	DM-B	DM-A	ULSD	DM-B
Viscosity [mm²/s]	171@50°C	3.3 @40°C	6.4 @40°C	2.6 @40°C	2.6@40°C	6.1@40°C
Density @ 15 °C [kg/m³]	975	877	878	830	835	813
Hydrogen [% mass]	10.63	12.59	12.40	13.20	13.8	12.9
Carbon [% mass]	87.16	86.86	85.80	86.64	85.8	86.2
Sulfur [% mass]	1.90	0.45	1.79	0.07	5.4 ppm	3340 ppm
Nitrogen [% mass]	0.31	0.10	0.01	0.09	0.0036	0.023
Ash [% mass]	0.01	0.01	0.01	0.01	0.005	0.002
Lower Heat Value Hu [kJ/kg]	40756	42330	42159	43317	42935	42462
Flash point [°C]	-	-	-	-	69	92
Poly aromatics content [%mass]	-	-	-	-	3	12.4

Methods

Test engines

6L48/60A

C3 serial engine IMO Tier-I

Power: 1050 kW/cyl.

Speed: 500 - 514 rpm

Size: 6L - 18V

Stroke: 60 cm

Bore: 48 cm

8L21/31

C2 test engine

IMO Tier-III

Power: 200 - 220 kW/cyl.

Speed: 900 - 1000 rpm

Size: 5L - 9L

Stroke: 21 cm

Bore: 31 cm

Methods

In service measurement @ 15,000 operating hours

Type: Double Hull Tanker
Classification: American Bureau of Shipping (ABS)
Year built: 2004
Registry: USA
Length 287 m
GRT 110,693
DWT 185,286 MT
1.3 million barrels
Twin redundant propulsion system
4x 6L48/60A 25,200 kW
Engines under MDT maintenance contract

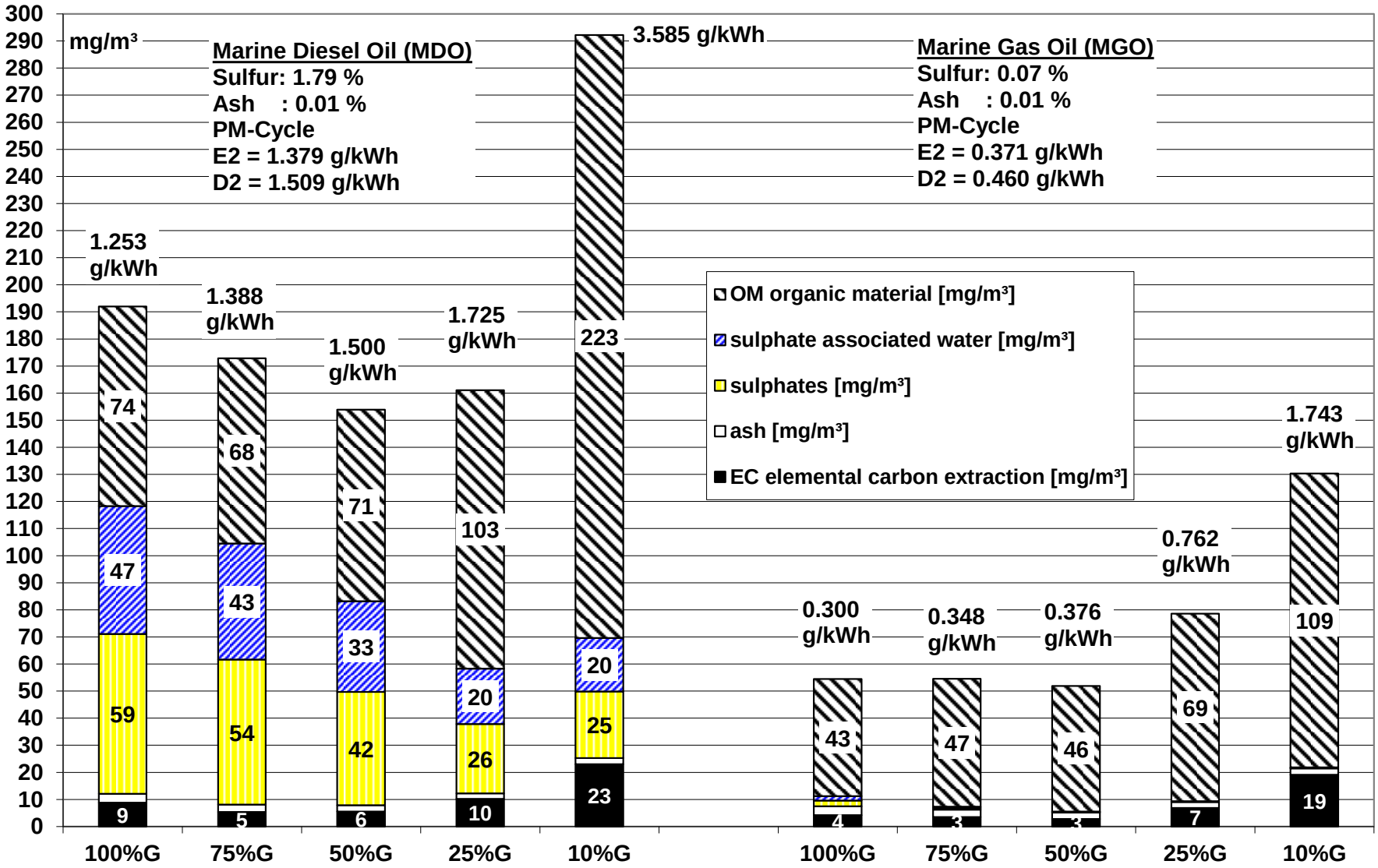
Picture from San Francisco Bay shows 1 main engine running on MDO @ anchor load ~1MW = 15% engine load

Methods

In service measurement set-up @ 15,000 operating hours

Results

PM emission & composition 6L48/60A #1130158 serial engine freshly manufactured on test bed (running in not finished)



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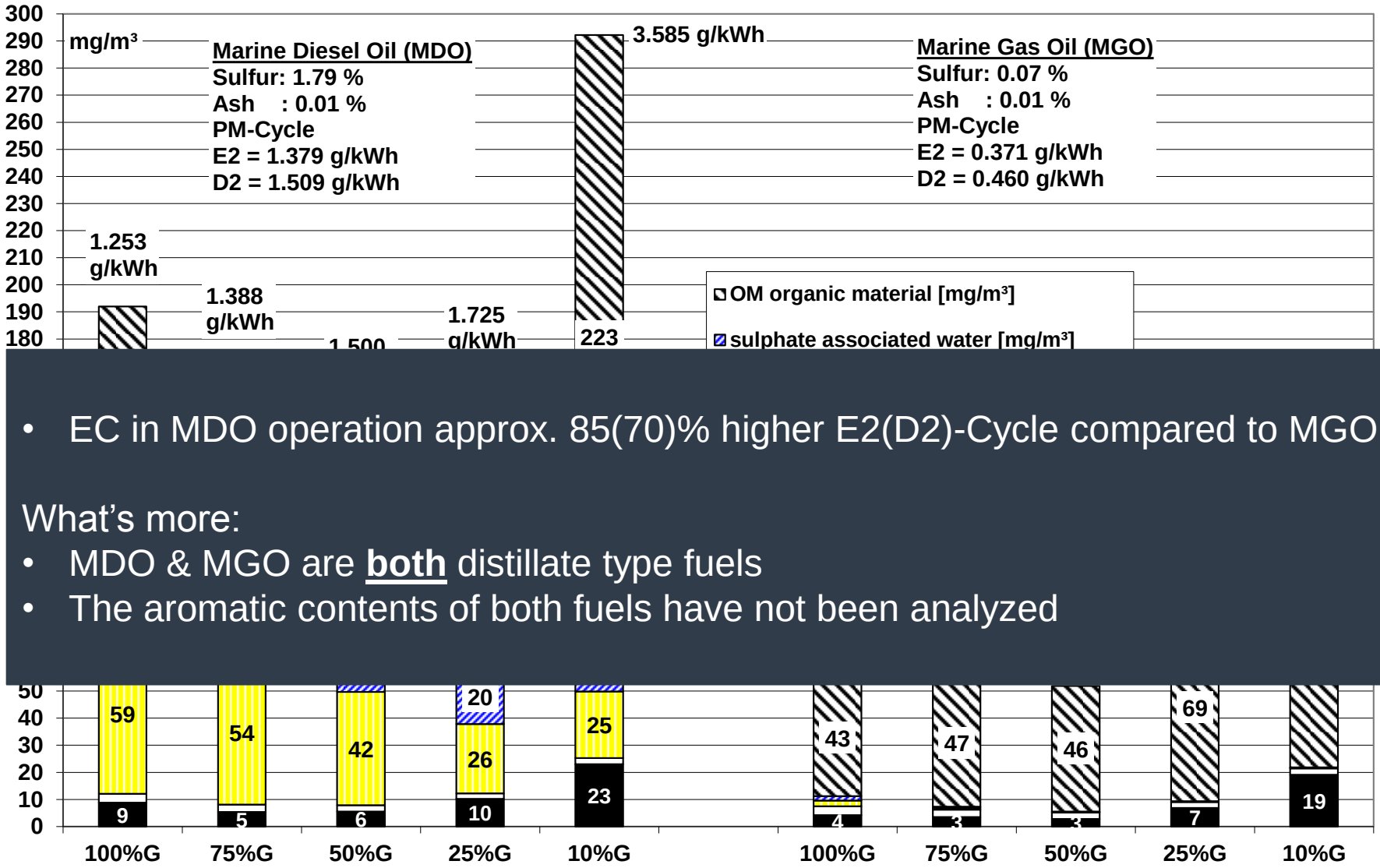


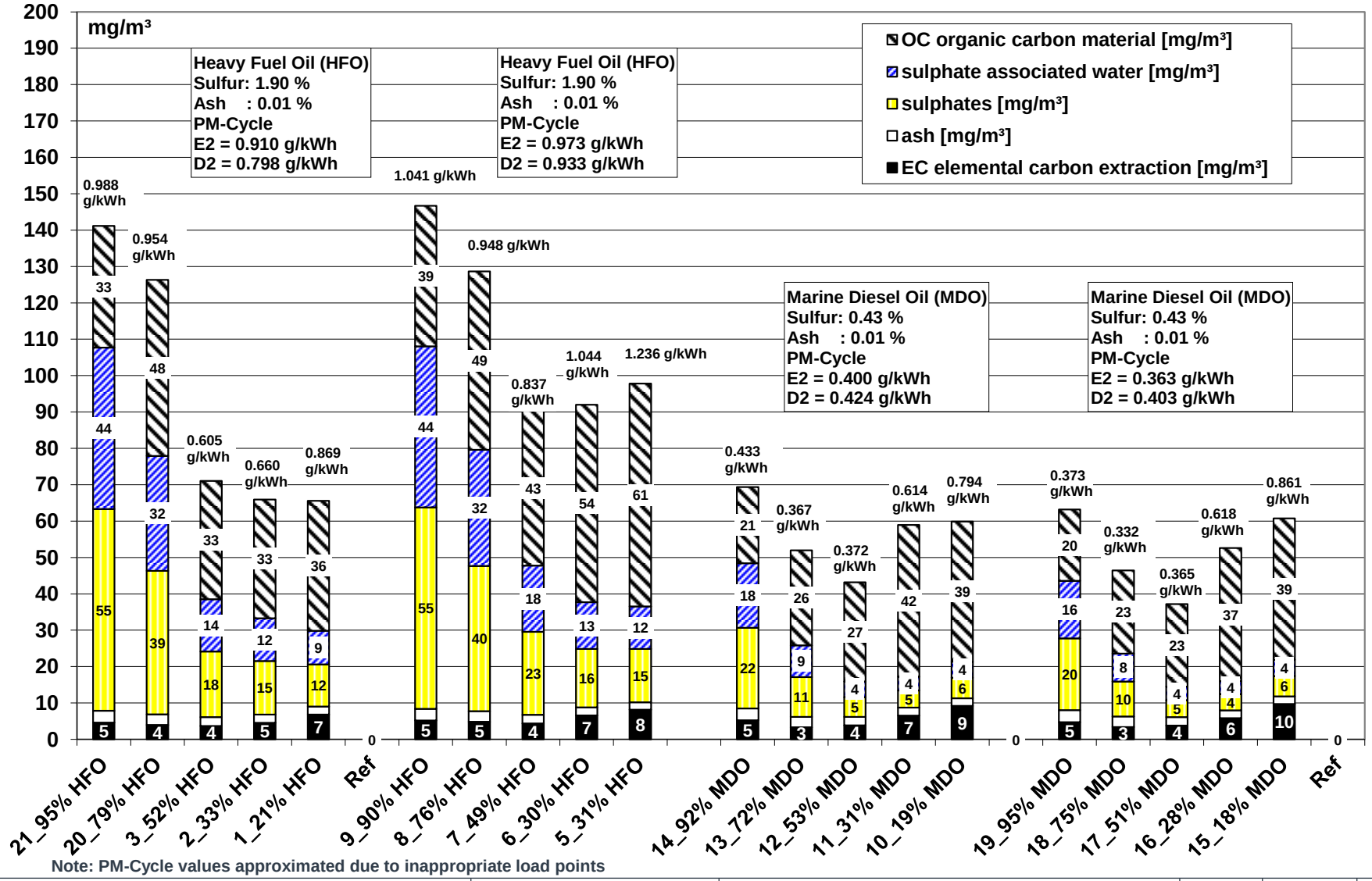
- EC in MDO operation approx. 85(70)% higher E2(D2)-Cycle compared to MGO

What's more:

- MDO & MGO are **both** distillate type fuels
- The aromatic contents of both fuels have not been analyzed

Results

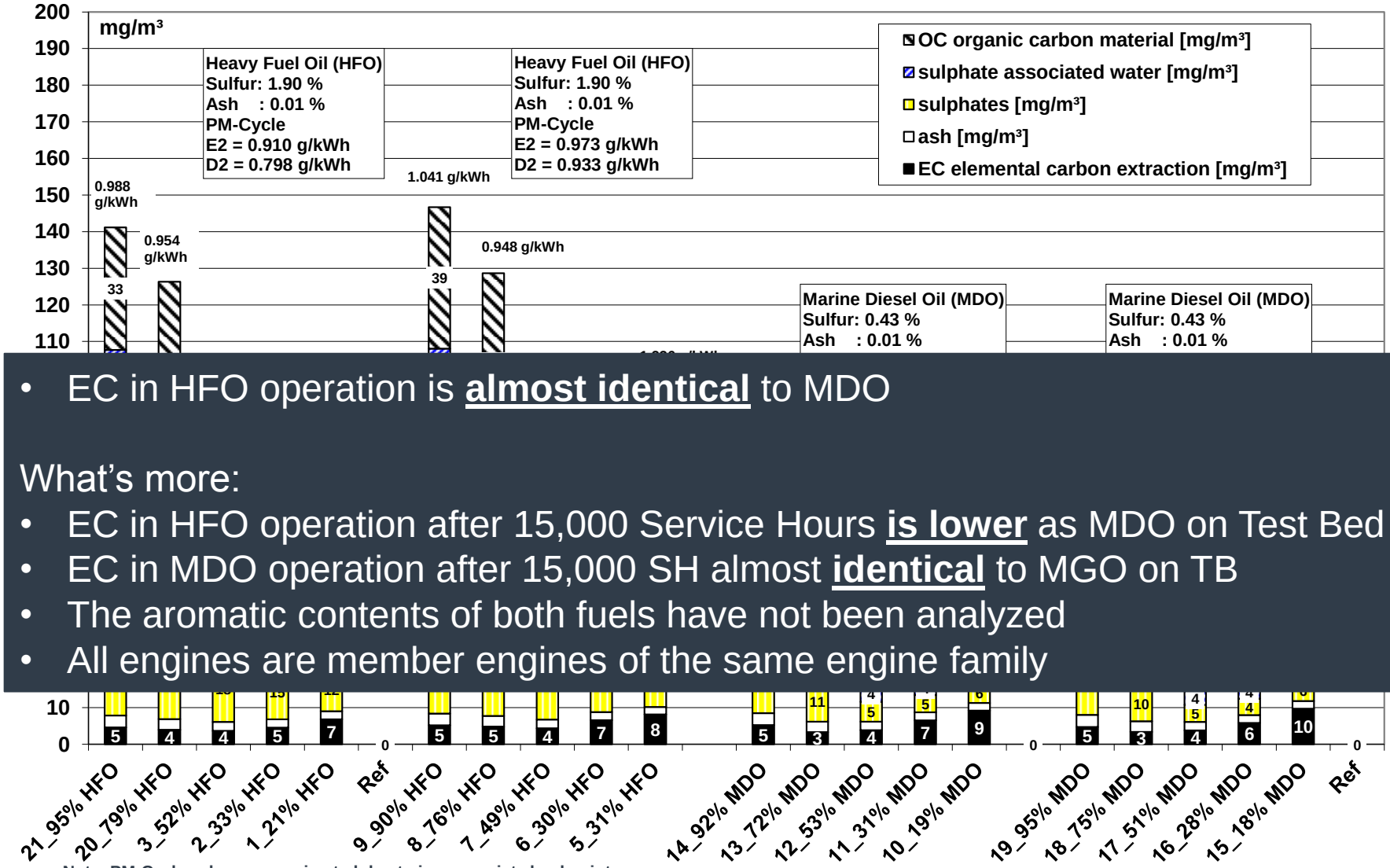
PM emission & composition 6L48/60A #1130127 & -128 after 15,000h in service, engines under MDT maintenance contract



Note: PM-Cycle values approximated due to inappropriate load points

Results

PM emission & composition 6L48/60A #1130127 & -128 after 15,000h in service, engines under MDT maintenance contract



- EC in HFO operation is **almost identical** to MDO

What's more:

- EC in HFO operation after 15,000 Service Hours **is lower** as MDO on Test Bed
- EC in MDO operation after 15,000 SH almost **identical** to MGO on TB
- The aromatic contents of both fuels have not been analyzed
- All engines are member engines of the same engine family

Note: PM-Cycle values approximated due to inappropriate load points

Results

6L48/60A engine family IMO supplement (parent & members)

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
STATEMENT OF COMPLIANCE
WITH REGULATION 13 OF ANNEX OF THE INTERNATIONAL
CONVENTION FOR THE PREVENTION OF POLLUTION FROM **SHIPS**

Manufacturer:	**MAN B&W Diesel AG**
Marine Diesel Engine Family:	**4MANM107.48D**
Certificate Number:	**MAN-IMO-04-01**
Date Issued	**8/11/2004**

Merrylin Zaw-Mon, Director
Certification and Compliance Division
Office of Transportation and Air Quality

This is to certify that the manufacturer of the above mentioned marine diesel engine has provided information to the U.S. Environmental Protection Agency that demonstrates:

1. this engine has been tested in accordance with the requirements of the Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines Engines, and,
2. the engine, its components, adjustable features, and Technical File, prior to the engine's installation and/or service on board a ship, fully comply with the applicable regulation 13 of Annex VI of the Convention

This Statement of Compliance is valid until Annex VI of Regulation 13 of the Convention is ratified and the requirements become effective and applicable to this engine.
Issued at U.S. Environmental Protection Agency, Office of Transportation and Air Quality, Washington, DC

Supplement to the Statement of Compliance with Regulation 13 of Annex VI of the International Convention on the Prevention of Pollution from Ships

1. Particular of the engine

1.1 Name & ddress of manufacter:
MAN **B&W** iesel AG
Stadtbachst 1
86224 **Augsburg**
Germany

1.2 Place of gine build:
do

1.3 Date of e gine build:
7/17/2002

1.4 Place of pre-certification survey:
do

1.5 Date of pre-certification survey:
07/17/2002

1.6 Engine family:
4MANM107.48D

1.7 Models:
6L 48/60, 1 130 125 (BP1)
6L 48/60, 1 130 127 (BP1)
6L 48/60, 1 130 128 (BP1)

6L 48/60, 1 130 129- 132 (BP2)

6L 48/60, 1 130 133- 136 (BP3)

6L 48/60, 1 130 158- 161 (BP4)

1.8 Test cycle:
E2 **Variable-Pitch and**
1.9 Rated Power(kW) **&** Speed(RPM):
6300 514
1.10 Engine certificate number:
MAN-IMO-04-01
1.11 Test fuel:
ISO 8217
1.12 NOx reducing device?:
No
1.13 Applicable **NOx** Emission Limit(g/kW-hr):
12.9
1.14 Engine **NOx** Emission Value(g/kW-hr):
10,0

2 Particulars of the Technical File:
2.1 Technical File number:
TF1130126 Parent engine
2.2 NOx verification number:
OBV1130126

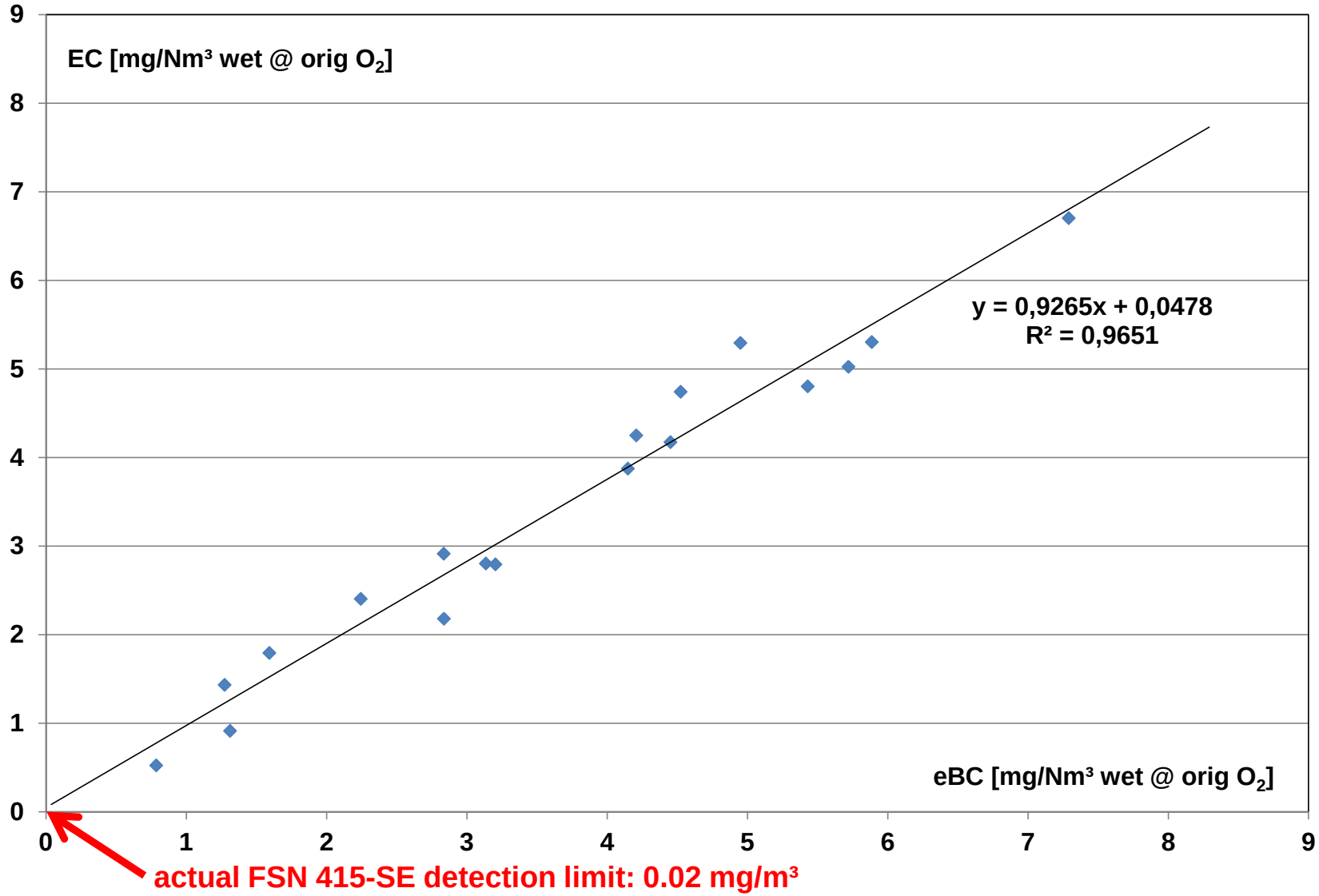
This is to certify that this record is correct in all respects. Issued at U.S. Environmental Protection Agency, Office of Transportation and Air Quality Washington, DC

Merrylin Zaw-Mon, Director
Certification and Compliance Division
Office of Transportation and Air Quality

AUG 11 2004
Date of Issue

Results (from 3rd ICCT workshop)

Correlation example EC (PM) vs. eBC (FSN) 21/31 EN-590 ULSD



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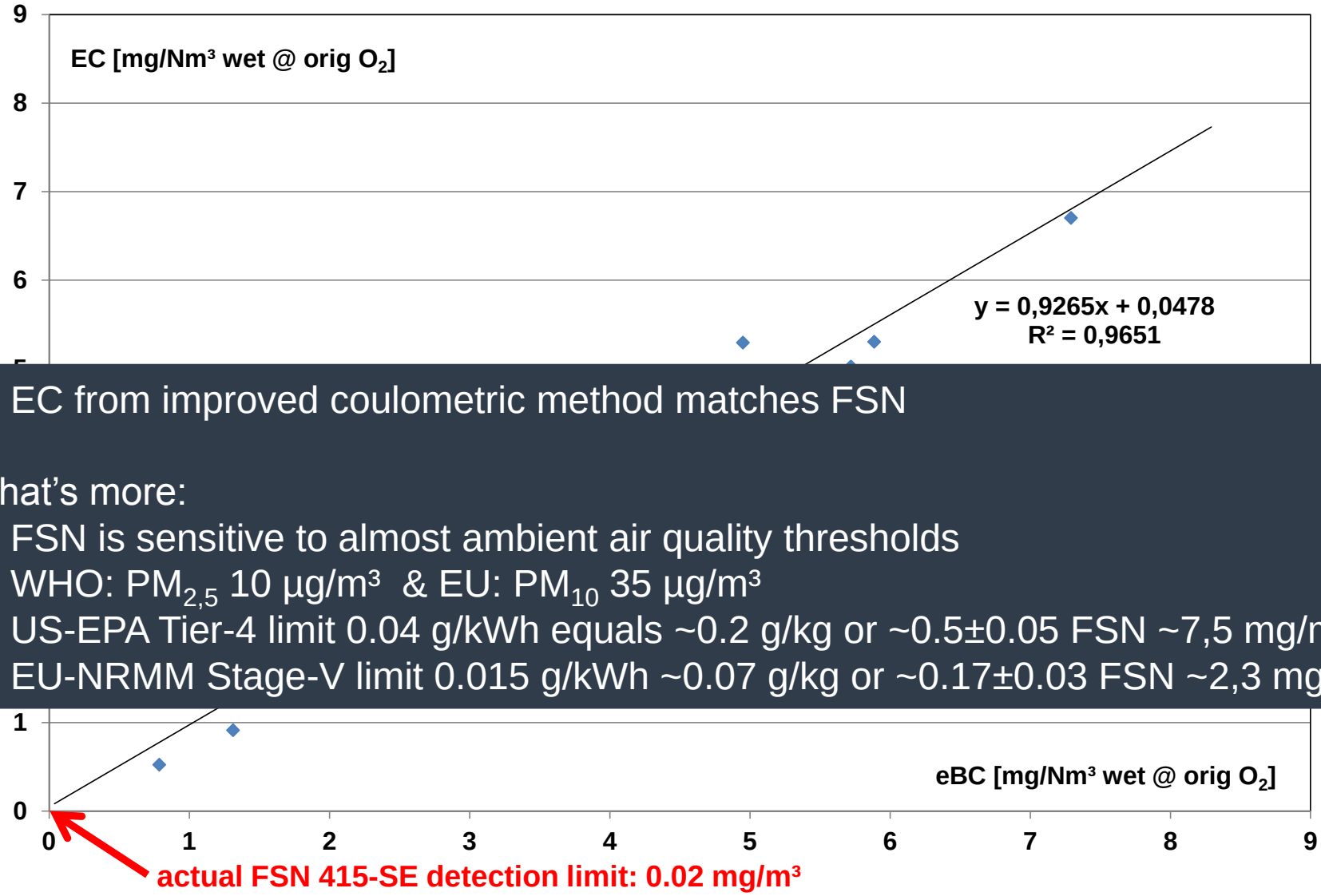


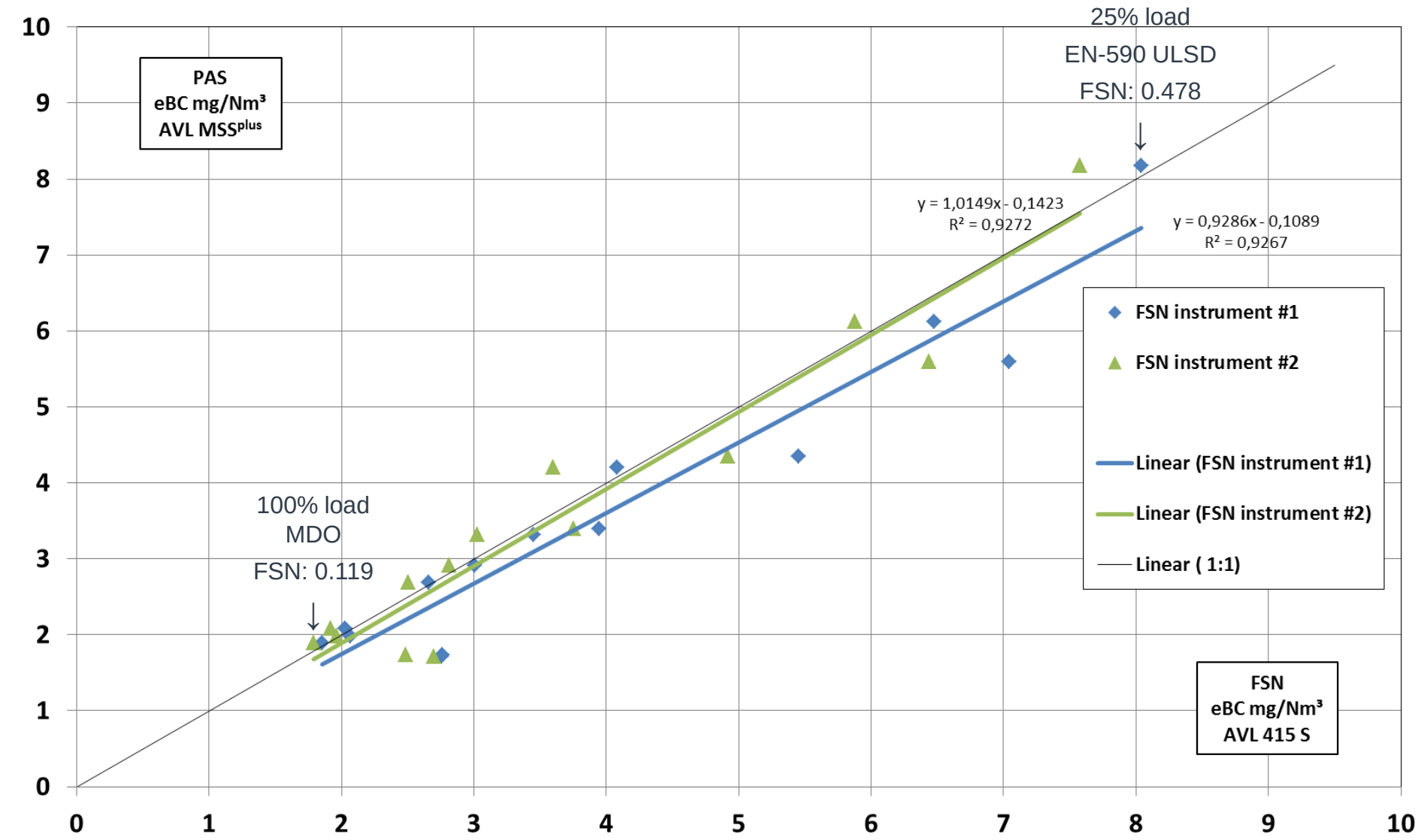
- EC from improved coulometric method matches FSN

What's more:

- FSN is sensitive to almost ambient air quality thresholds
- WHO: $PM_{2,5}$ 10 µg/m³ & EU: PM_{10} 35 µg/m³
- US-EPA Tier-4 limit 0.04 g/kWh equals ~0.2 g/kg or ~0.5±0.05 FSN ~7,5 mg/m³
- EU-NRMM Stage-V limit 0.015 g/kWh ~0.07 g/kg or ~0.17±0.03 FSN ~2,3 mg/m³

Results

Instrument comparison FSN vs. PAS 8L21/31 EN-590 & MDO



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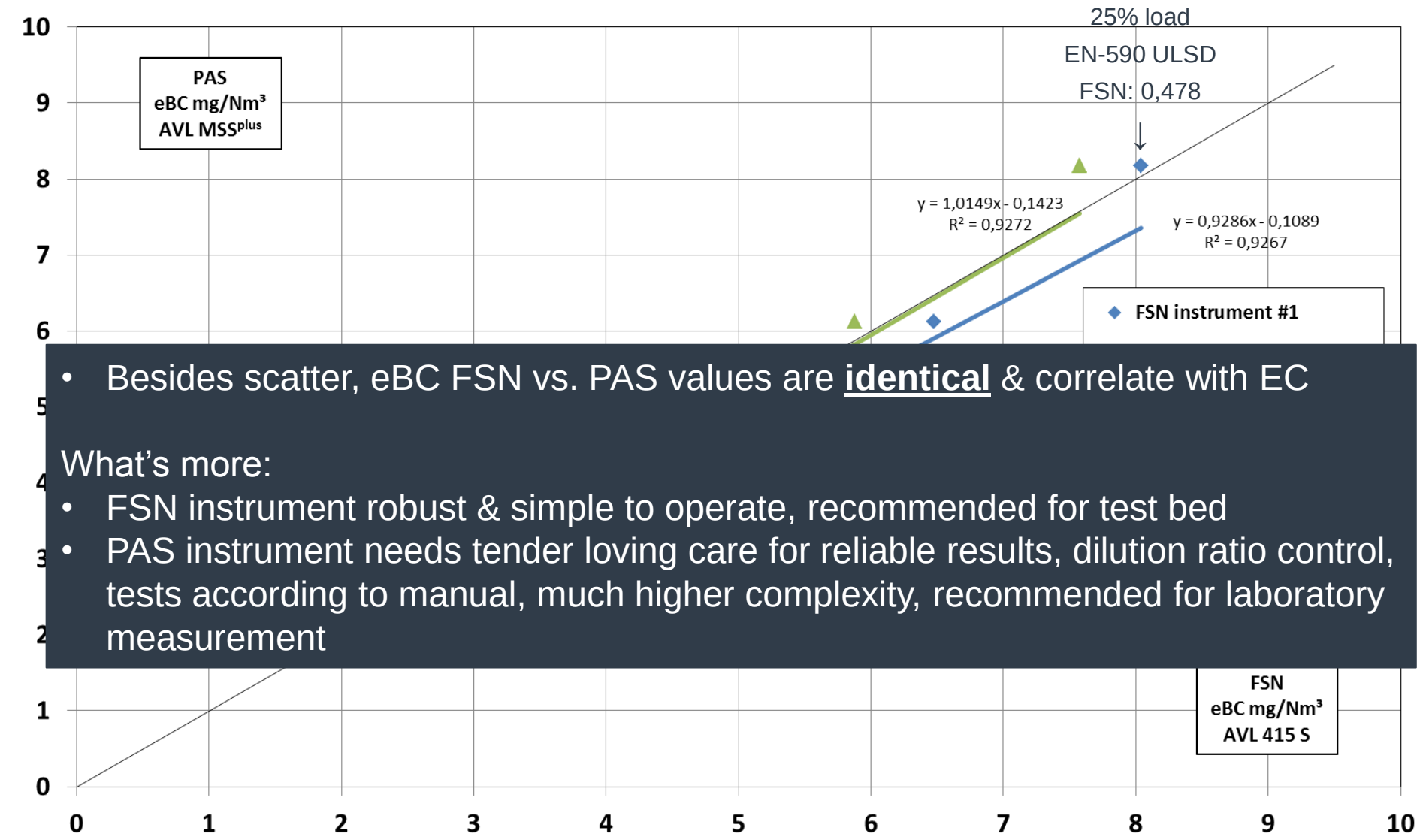


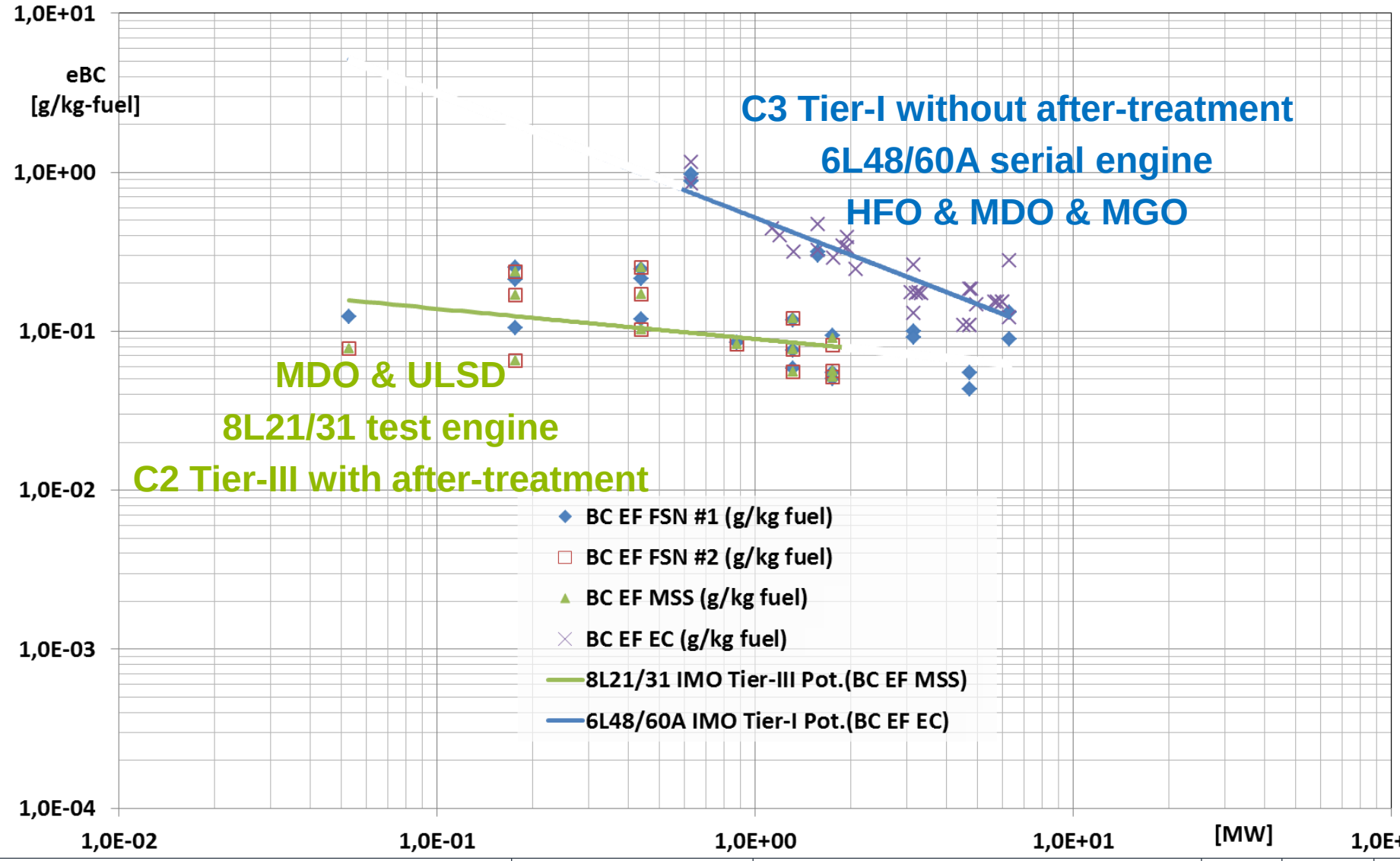
- Besides scatter, eBC FSN vs. PAS values are **identical** & correlate with EC

What's more:

- FSN instrument robust & simple to operate, recommended for test bed
- PAS instrument needs tender loving care for reliable results, dilution ratio control, tests according to manual, much higher complexity, recommended for laboratory measurement

Results

eBC in g/kg fuel 8L21/31 Tier-III test vs. 6L48/60A Tier-I serial



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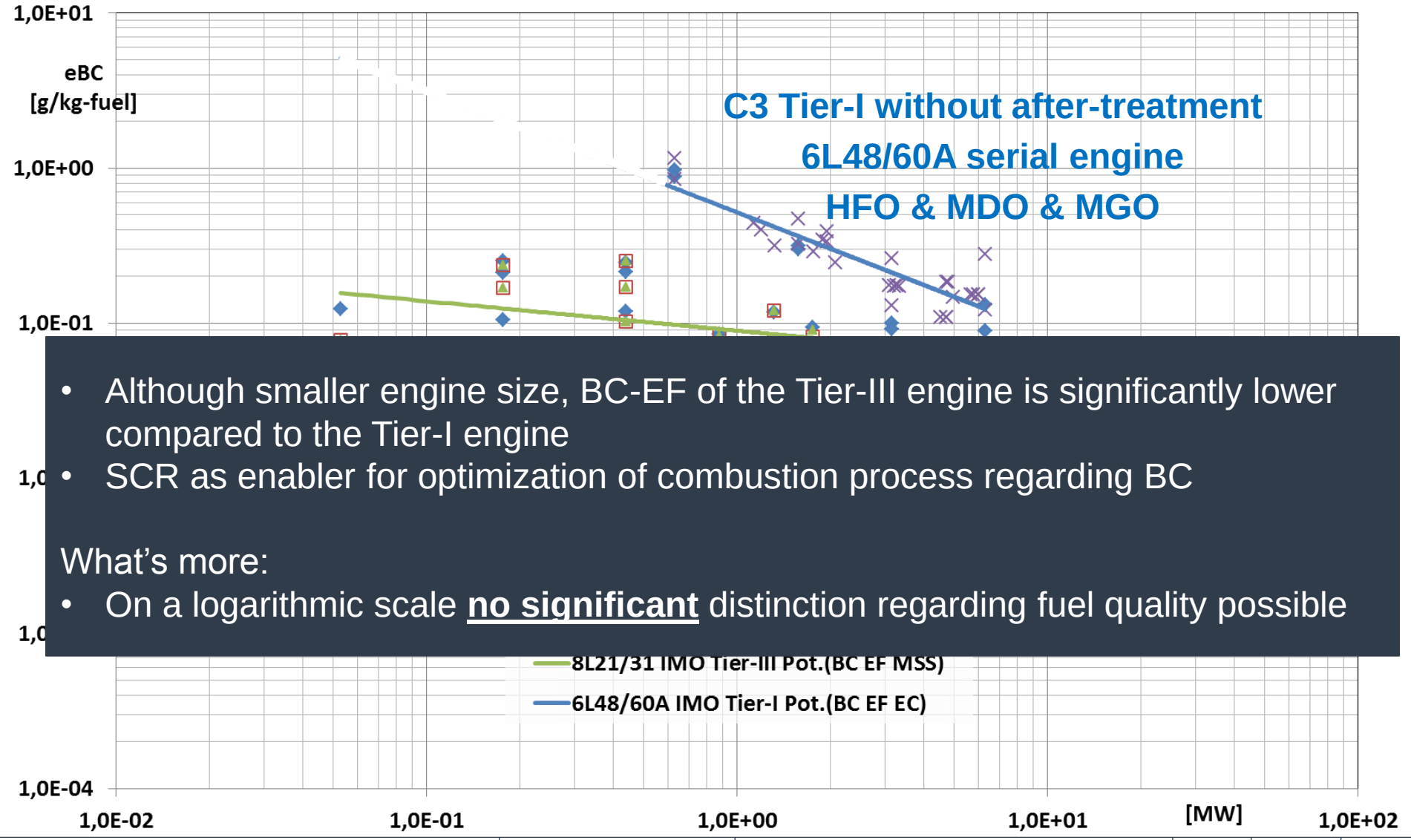


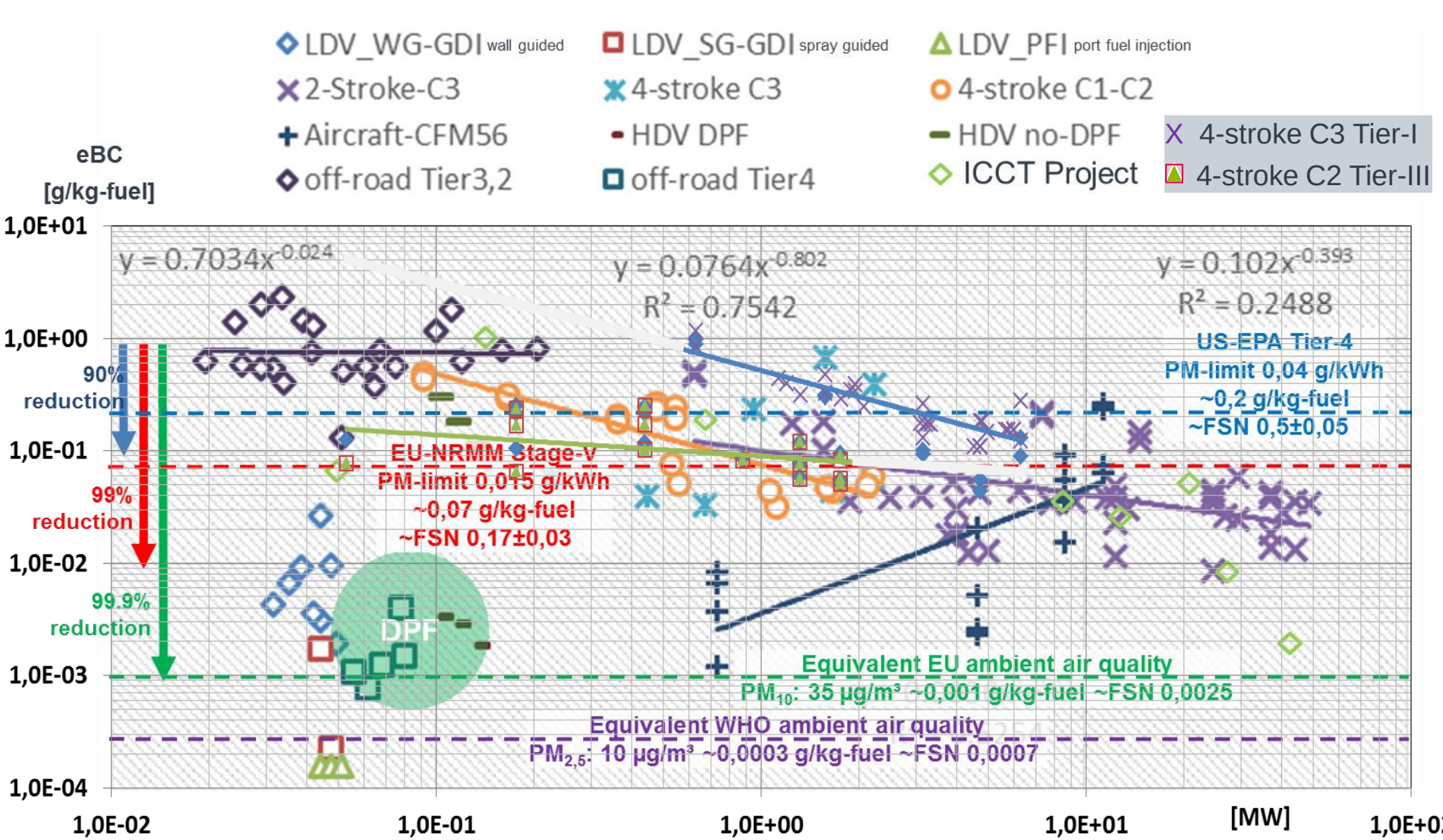
- Although smaller engine size, BC-EF of the Tier-III engine is significantly lower compared to the Tier-I engine
- SCR as enabler for optimization of combustion process regarding BC

What's more:

- On a logarithmic scale **no significant** distinction regarding fuel quality possible

Results

eBC in g/kg fuel vs. UCR-ICCT database put into regulatory context



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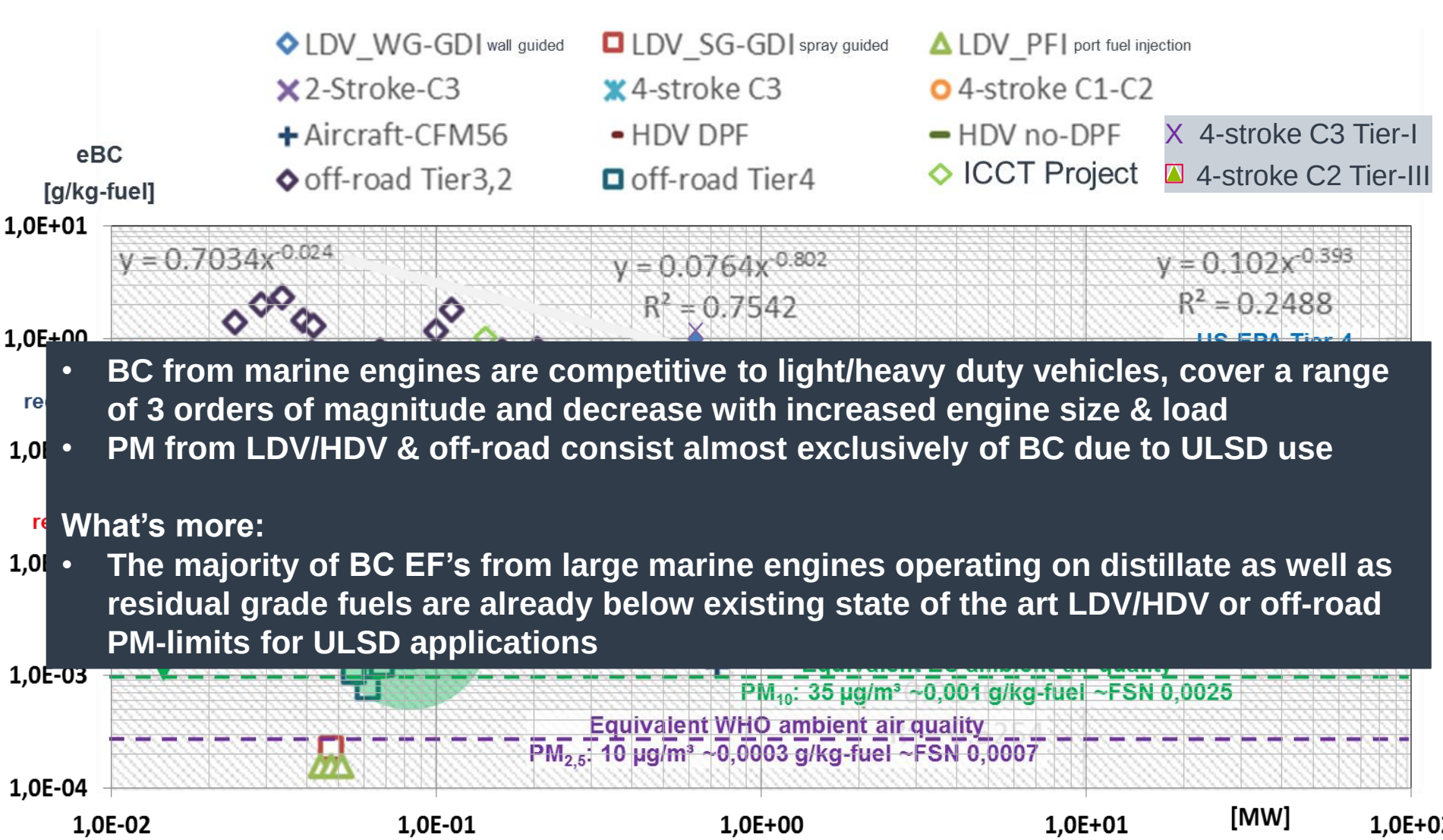

- **BC from marine engines are competitive to light/heavy duty vehicles, cover a range of 3 orders of magnitude and decrease with increased engine size & load**
- **PM from LDV/HDV & off-road consist almost exclusively of BC due to ULSD use**

What's more:

- **The majority of BC EF's from large marine engines operating on distillate as well as residual grade fuels are already below existing state of the art LDV/HDV or off-road PM-limits for ULSD applications**

Conclusions

Measurement methods, engine conditions & fuels

No deterioration of PM or eBC emission found after 15,000 operating hours in service, provided that the engines are maintained according to the manufacturers guidelines

Large differences in BC emissions already exist within the distillate fuel type

Under controlled conditions, difference between FSN, PAS & EC methods are negligible

- **The actual fuel quality (e.g. aromatic content) and <u>not the fuel type</u> (residual vs. distillate) plays the key role**
- **FSN is sensitive even for very low BC emissions**
- **Compared to any other method, FSN emerged as most robust & accurate method [IMO PPR 1/8/3]**

SCR application acts as enabler for combustion optimization for improved BC

LII & MAAP not further recommended due to reported challenges in other studies

Acknowledgements & References

Acknowledgements:

Alaska Tanker Company (ATC), Portland, Oregon, USA, for in service measurement opportunity

References:

AVL 415 SE: https://www.avl.com/-/avl-smoke-meter

AVL 483 MSS^{plus}: https://www.avl.com/-/mssplus-avl-micro-soot-sensor

AVL 472 Smart Sampler: https://www.avl.com/-/avl-smart-sampler

IMO PPR 1/8/4: Proposed measurement method for Black Carbon: Determination of Elemental Carbon from PM Filter Samples (DNV-GL in-house method), EUROMOT submission.

IMO PPR 1/8/3: Proposed measurement method for Black Carbon, EUROMOT submission.

UCR-ICCT: UCR, Measure Marine BC Emissions, ICCT 3rd Workshop, 2016

Kent Johnson, Marine BC EF, ICCT 2nd Workshop, 2015

Disclaimer

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This data serves informational purposes only and is especially not guaranteed in any way. Depending on the subsequent specific individual projects, the relevant data may be subject to changes and will be assessed and determined individually for each project. This will depend on the particular characteristics of each individual project, especially specific site and operational conditions.

Do you have any more questions?

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