Emission and chemical composition of PM from medium speed 4-stroke marine Diesel engines for different fuels

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Keywords: Particulate matter, combustion aerosols, measurement, characterization, chemical composition, sulfur and carbonaceous particles, volatile and nonvolatile fraction.

Compared to gaseous emission components (Lauer, 1999) there is only limited knowledge available today of particulate emission from marine Diesel engines. The emission of particulates in the marine environment, the detailed chemical composition and aerosol properties are widely unknown. Detailed particulate emission measurements and chemical analysis have been performed on large medium speed four stroke Diesel engines for different types of fuel.

The particulate matter (PM) was measured according to ISO-8178 with a dilution system and the PM was collected on quartz fiber filters for chemical characterization. The PM constituents have been analyzed by Germanischer Lloyd (GL) for elemental carbon (EC) and organic carbon (OC) thermographically and for sulfates (SO_4) ionchromatographically. The sulfate bound water (H_2O) and organic material (OM) has been calculated from the analyzed sulfates and organic carbon. The ash constituents have been calculated from the fuel ash content. The PM number and size distribution was measured by Deutsches Zentrum für Luft- und Raumfahrt (DLR). Finally the fuel properties have been analyzed.

The dilution system is a special version of the AVL-472 Smart Sampler for mobile application. It has to be noted that according to the ISO-8178 standard, the dilution measurement technique is only validated up to 0.8% sulfur in the fuel.

Several measurement instruments have been applied for the size characterization of the particulates. After a primary heated and a secondary unheated dilution stage the sample was divided into a differential mobility analyzer (DMA) coupled to a condensation particulate counter (CPC) to cover the range from 10 – 300 nm. The second path was routed via an additional dilution stage and an optional Thermodenuder to an online battery of diffusion screen separators (Feldpausch *et al.*, 2005) for the 30 – 100 nm range and to a multi-channel condensation particle size analyzer (CPSA) (Stein *et al.*, 2001) for the range of 4 – 20 nm. Additionally, a multi-angle absorption photometer (Petzold & Schönlinner, 2004) was applied for online elemental carbon measurements.

The typical fuel used in marine transport is residual fuel oil e.g. heavy fuel oil (HFO), which is a waste product from refinery processes. Due to the superior mechanical efficiency of large Diesel engines compared to other combustion processes it is an ideal utilization. The mean sulfur content of these fuels is in the range of 2.7% (Kassinger, 2005). For so called "SO_x Emission Control Areas" like the Baltic Sea a maximum sulfur content of 1.5% is allowed according to IMO regulations (IMO MARPOL 73/78 Annex VI, 1997). It is expected that residual fuels will persist as the main fuel for ship propulsion in the future.

The characteristic values of the fuels have been analyzed. Besides residual fuels also distillate fuels have been investigated. The sulfur contend was in the range from 1 ppm for the Swedish Clean Fuel up to 3.47 % for the HFO. At the same time the ash contend was in the range from 0 for the Swedish to 0.04 % for the HFO.

Four different medium speed 4-stroke Diesel engines and one high speed Diesel engine for comparison have been tested. The dimensions of such engines can be realized very impressively at the occasion when a large one is loaded to a barge.

The PM emission from a large medium speed marine Diesel engine consists mainly of volatiles like organic material, sulfate bound water and sulfates. Different fuels show significantly different amounts of sulfates, sulfate bound water and ash. The detailed PM emission and chemical composition for different load points of the 16/24, 21/31, 32/40 and 48/60 engines and for different fuels e.g. HFO, Marine Diesel Oil (MDO), Marine Gas Oil (MGO) and Swedish Clean Fuel are displayed. A lower fuel oil quality leads to an increased particulate emission. The composition characteristic of the particulates of the large engines show no significant change depending on the engine size. Contrary to that the chemical composition of the high speed EURO III truck derived marine Diesel engine consist mainly of non volatile compounds like elemental carbon and ash. For a comparable fuel oil quality like MGO or the Swedish Clean Fuel the absolute elemental carbon emissions of the large Diesel engines are in the same range as for the small high speed engine.

The number size distribution combined from all the sizing techniques show a strong nucleation and Aitken mode that overlaps the accumulation mode and the employment of the Thermodenuder confirms the high amount of volatiles of the particulates for 100% load.

In summary the particulate composition of large medium speed Diesel engines consist mainly of volatile material and the fuel composition has a great influence on the composition as well. One of the next steps in the ongoing project is to find a conversion efficiency for the fuel sulfur to sulfate-particulates. Some questions arises as the composition of the particulates from large medium speed Diesel engines differ significantly from small high speed Diesel engine particulates as well as the used fuels differ. Can the same effects be expected from these particulates, do the same limits have to be faced in the future and will the same measurement techniques be applicable?

Acknowledgements

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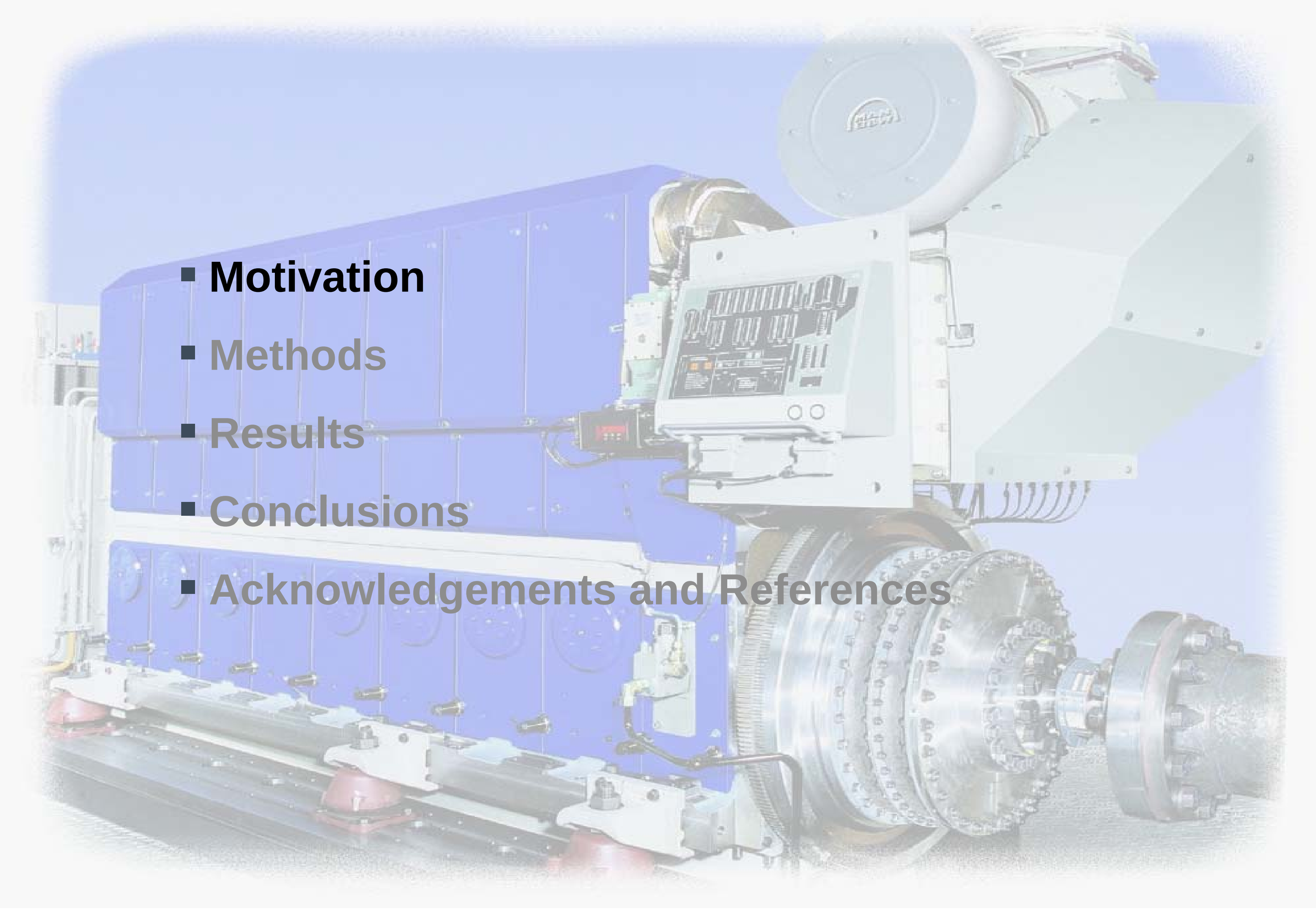
MAN B&W Diesel

Outline



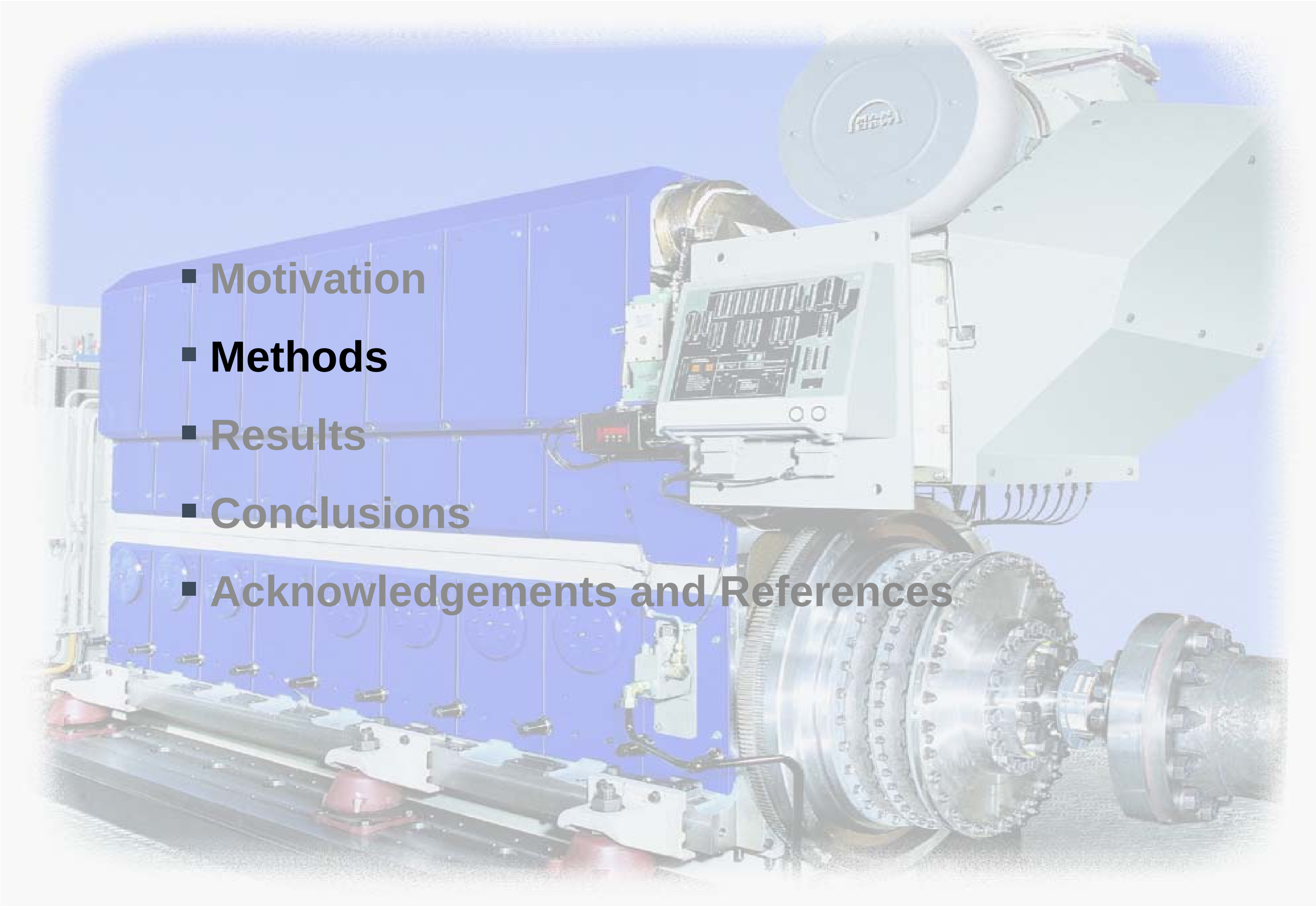
- **Motivation**
- Methods
- Results
- Conclusions
- Acknowledgements and References

Motivation

- **Limited knowledge available today of PM emissions from large four-stroke medium speed Diesel engines for ships compared to Diesel passenger cars and trucks**

- **Detailed chemical composition and aerosol properties of the PM from marine Diesel engines are widely unknown**

- **Investigation of the influence of different types of fuel on the PM**



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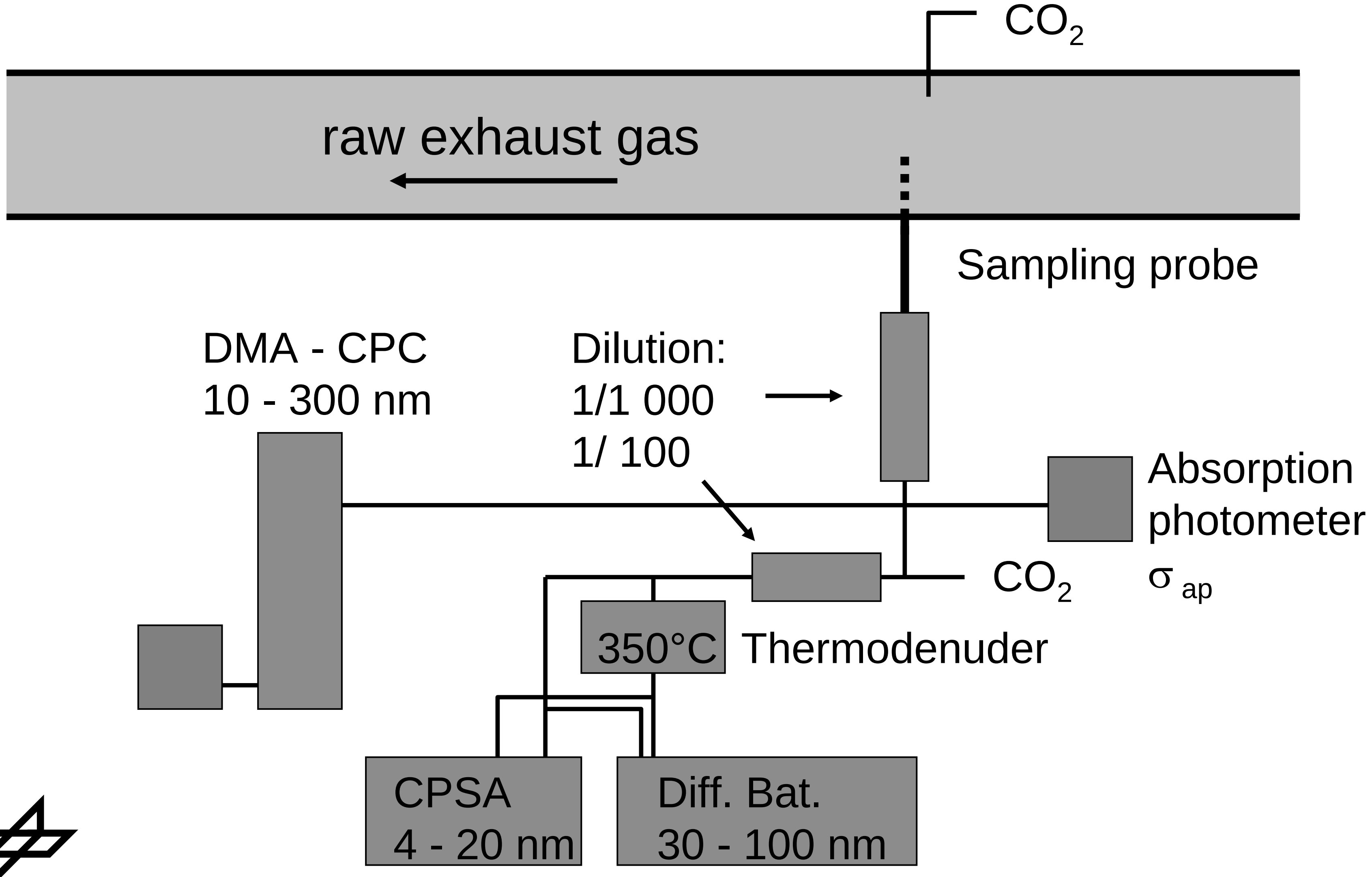
Measurement methods

- **Particulate measuring according to ISO-8178 performed by MAN B&W Diesel AG (MBD) with AVL 472 Smart Sampler Modular dilution system**
- **Chemical analysis of the PM performed by Germanischer Lloyd (GL) thermographically and ionchromotographically**
- **PM number size distribution measured by Deutsche Luft und Raumfahrtgesellschaft (DLR) with differential mobility analyzer, online diffusion battery, multi-channel condensation particulate counter and with / without Thermodenuder**
- **Fuel analysis performed by MBD**

Mobile particulate measuring system

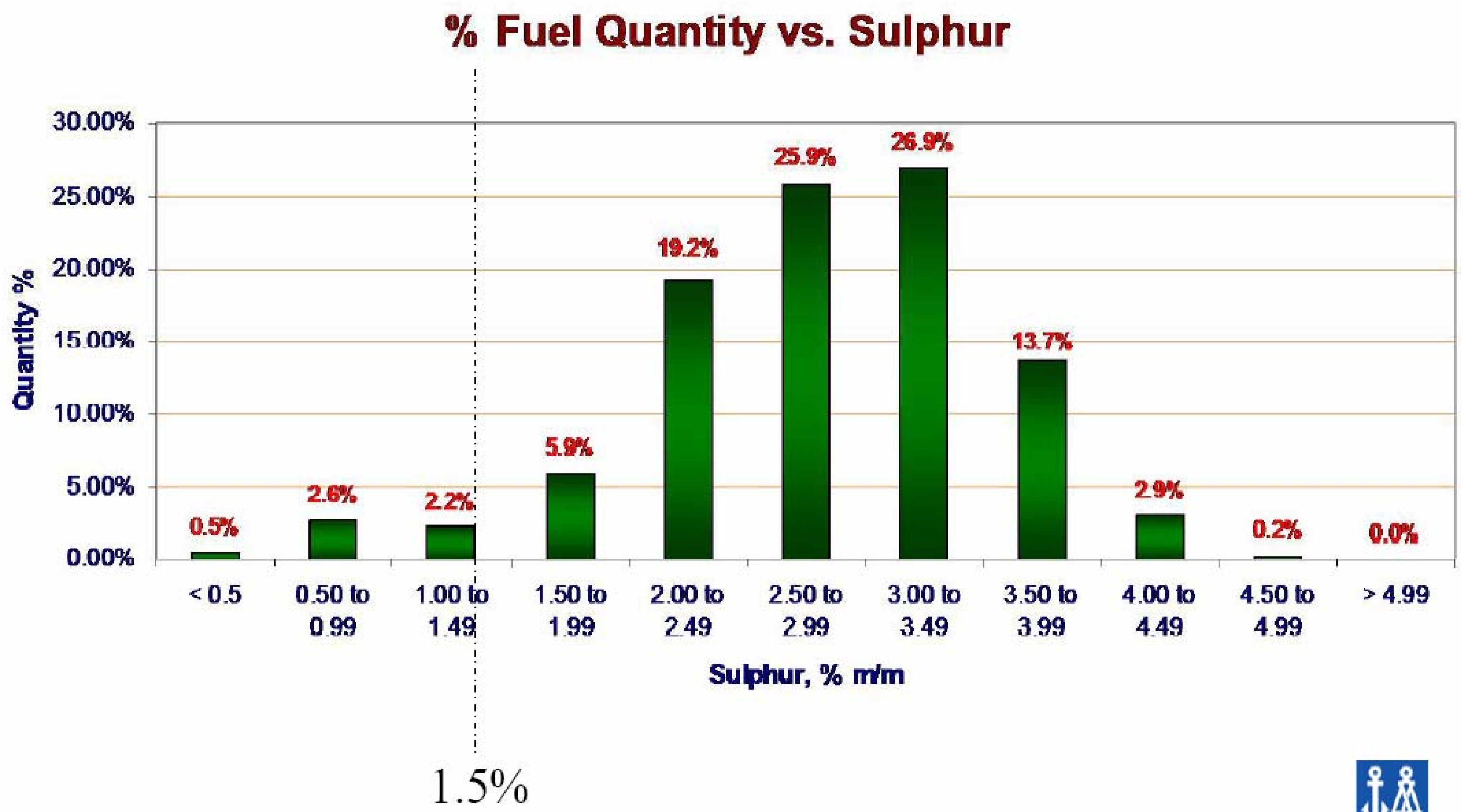
- **Remark: Particulate measuring according to ISO-8178 is conclusively proven to be effective for fuel sulfur levels up to 0.8 w% only**

Mobile aerosol measuring system



Quality of bunker oil for ships

2004 Worldwide fuel sulphur distribution



MANAGING RISK DNV

Fuel oil properties

Fuel	Heavy Fuel Oil (HFO)			Marine Diesel Oil (MDO)
Category	residual	residual	residual	distillate
Type	A	B	C	-
Viscosity [mm²/s]	880 @ 50°C	422 @ 50°C	247 @ 50°C	6.4 @ 40°C
Density @ 15°C [kg/m³]	985	985	976	879
Hydrogen [%-mass]	10.55	10.63	11.1	12.43
Carbon [%-mass]	85.61	86.73	86.8	85.79
Sulfur [%-mass]	3.47	2.29	0.76 (7600 ppm)	1.73
Nitrogen [%-mass]	0.37	0.44	0.35	0.05
Ash [%-mass]	0.04	0.04	0.01	0.01
Lower Heat value Hu [kJ/kg]	40198	40318	40884	42007

Fuel	Marine Gas Oil (MGO)		2004 Petrol Station Diesel	Swedish Clean Fuel
Category	distillate	distillate	distillate	distillate
Type	A	B	-	-
Viscosity [mm²/s]	3.3 @ 40°C	2.7 @ 40°C	2.4 @ 40°C	2 @ 40°C
Density @ 15°C [kg/m³]	841	831	833	813
Hydrogen [%-mass]	13.2	13.35	13.47	13.9
Carbon [%-mass]	86.2	86.48	86.48	85.9
Sulfur [%-mass]	0.00398 (40 ppm)	n. a.	n. a.	0.00012 (1 ppm)
Lower Heat value Hu [kJ/kg]	43099	43119	42910	43430

4-stroke Diesel engines specifications

Type	48/60	32/40	21/31	16/24	truck engine
Category	large medium speed Diesel engine				small high speed
Cylinder Order	6 cylinder in line	7 cylinder in line	8 cylinder in line	9 cylinder in line	12 cylinder V-type
Power [kW]	6300	3360	1720	990	1000
Speed [rpm]	514	750	1000	1200	2300
Bore [mm]	480	320	210	160	128
Stroke [mm]	600	400	310	240	142
Compression ratio [-]	14.4	14.5	15.5	15.7	15.5

Investigated Diesel engine types comparison of size

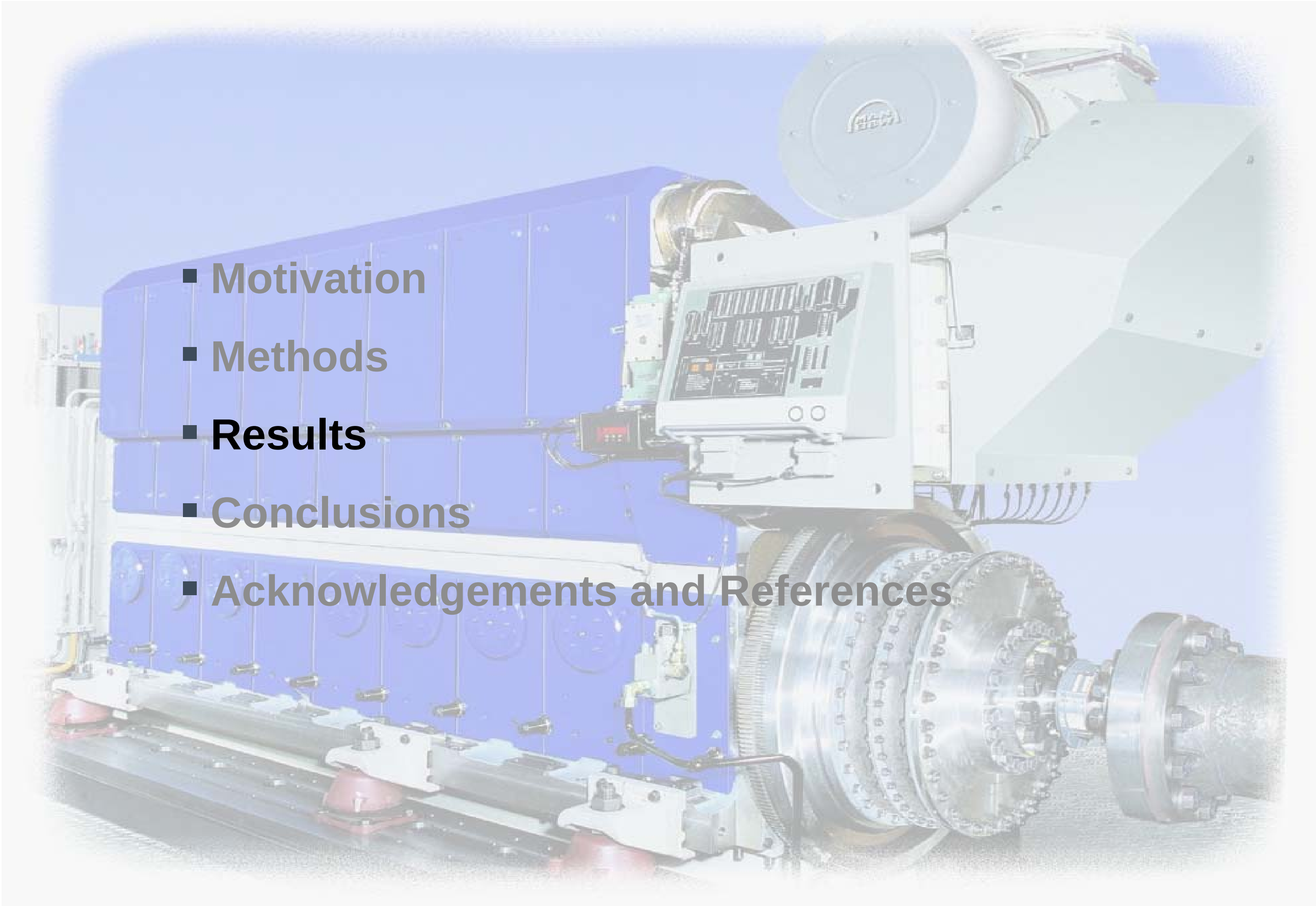
12510 kW

12.6 m long

5.14 m high

3.55 m wide

213 t dry mass



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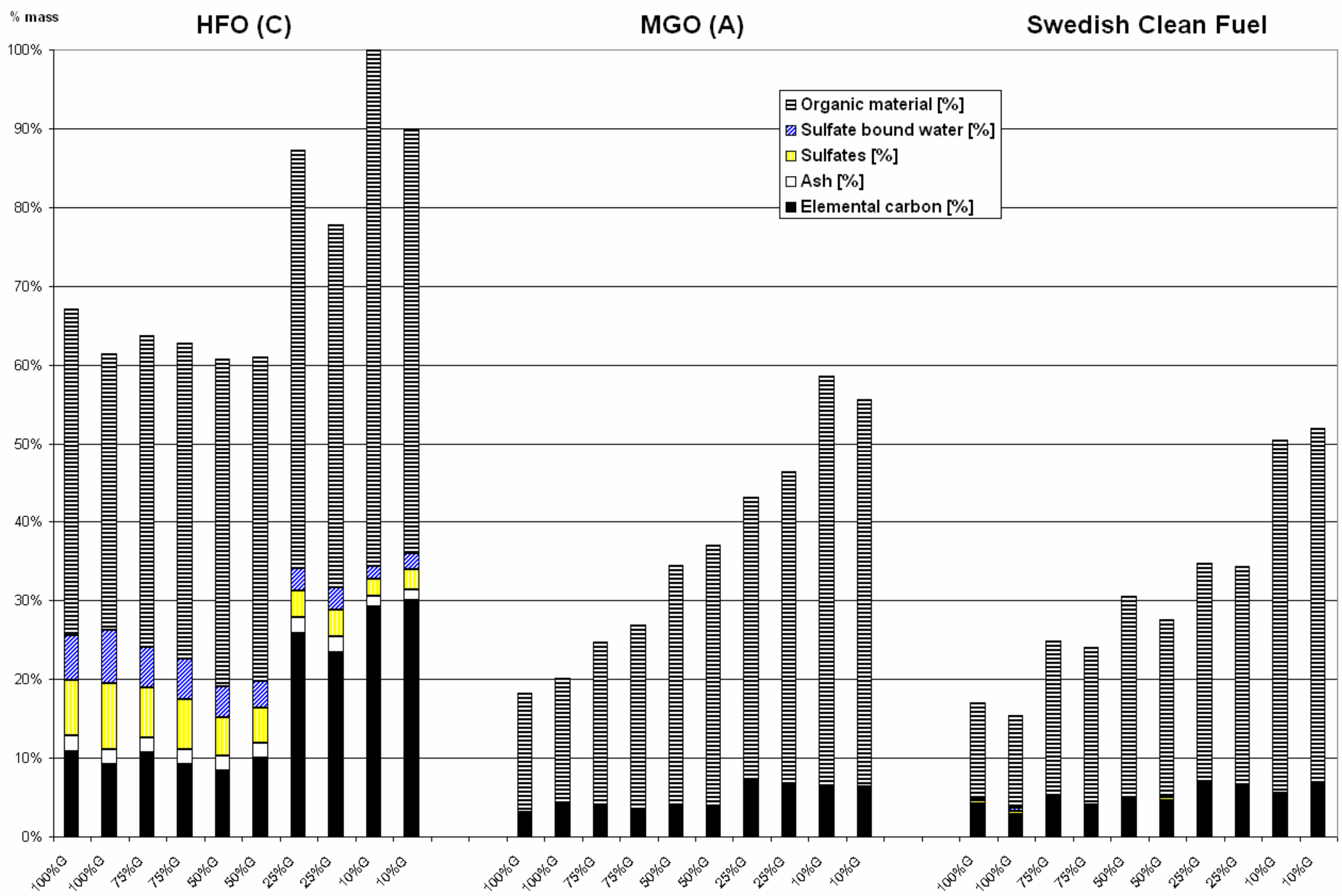
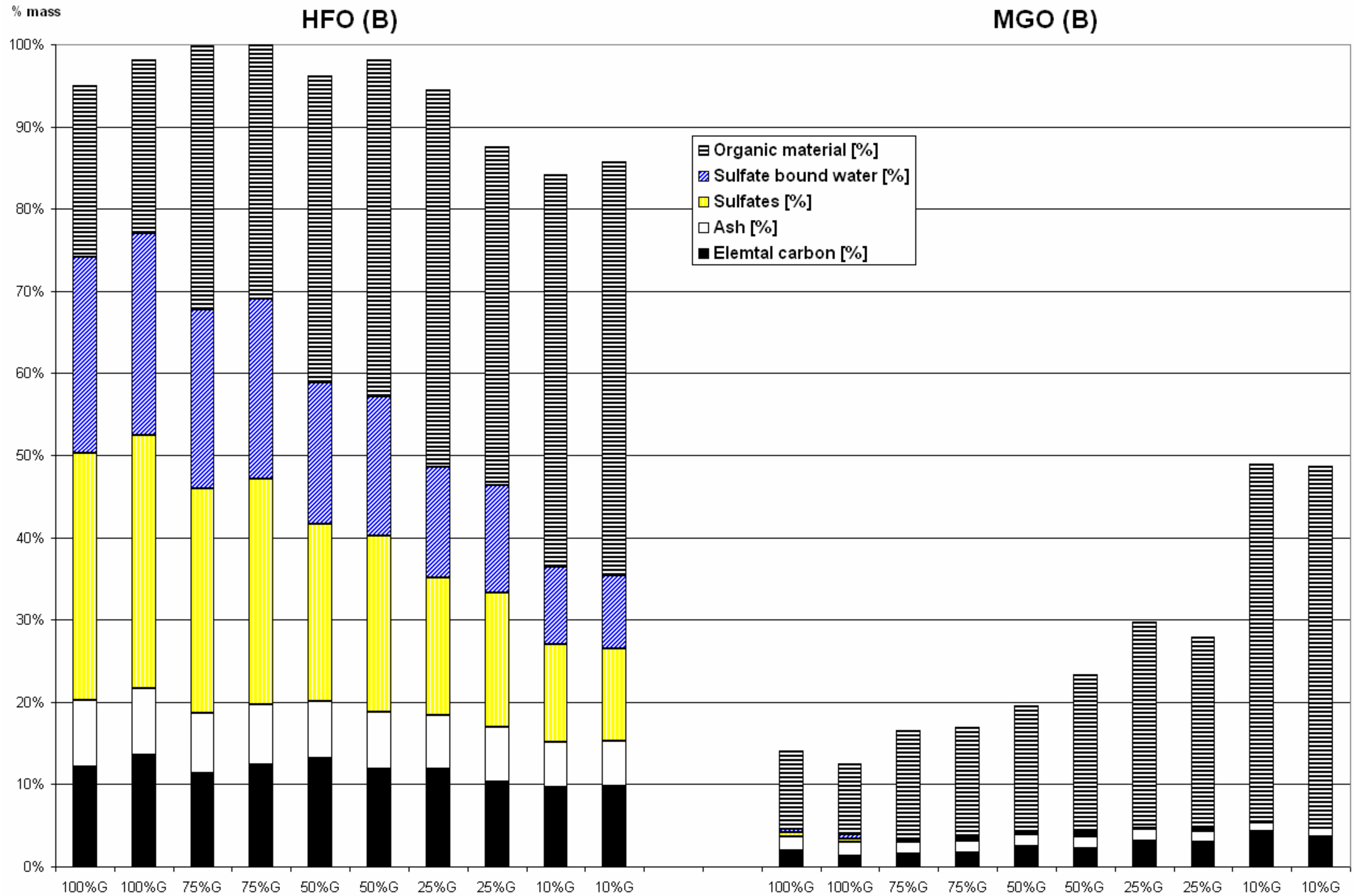
16/24 engine: PM emission and composition for 3 different fuels

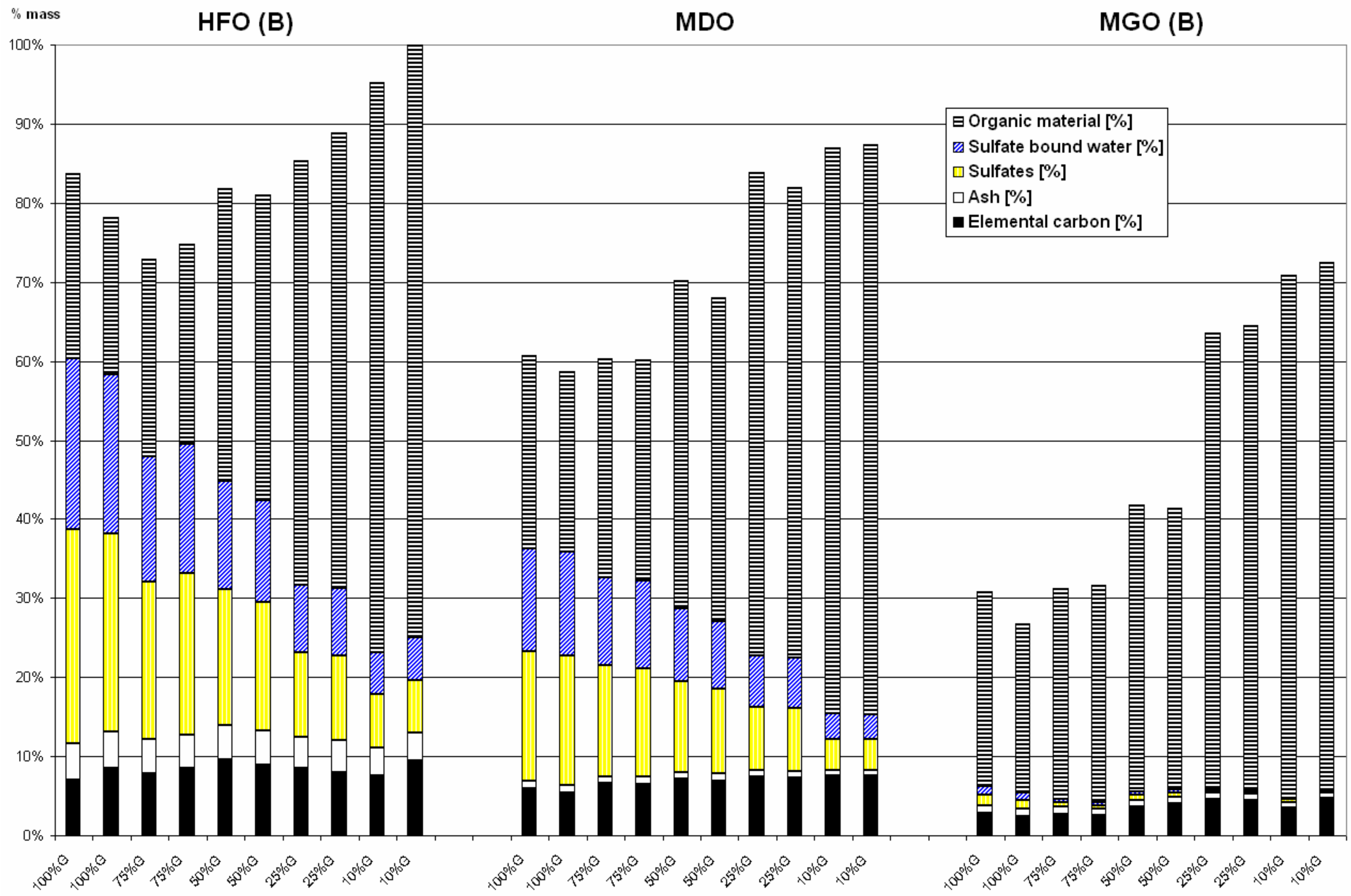


21/31 engine: PM emission and composition for 2 different fuels

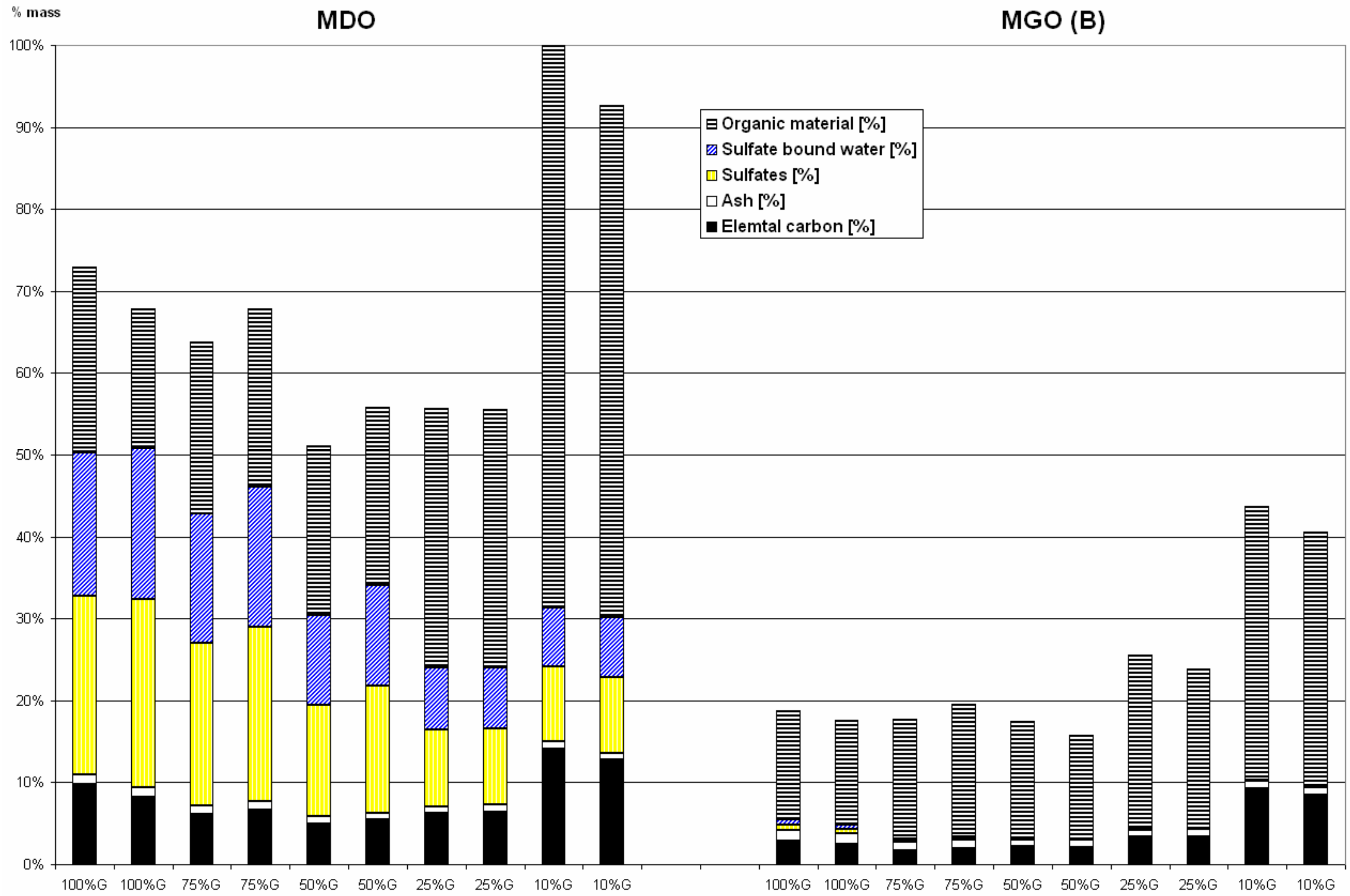


MAN B&W Diesel

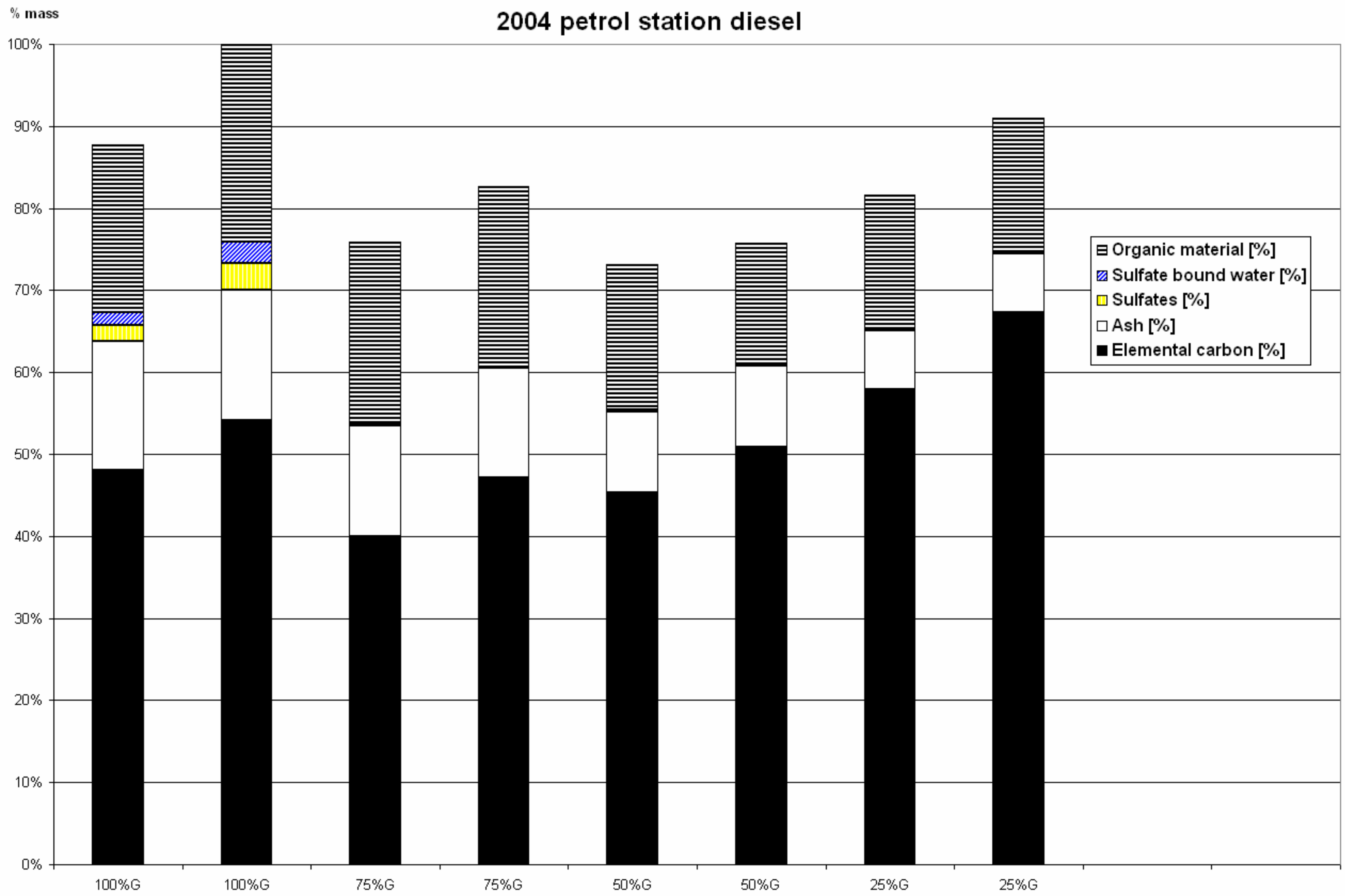
32/40 engine: PM emission and composition for 3 different fuels



48/60 engine: PM emission and composition for 2 different fuels

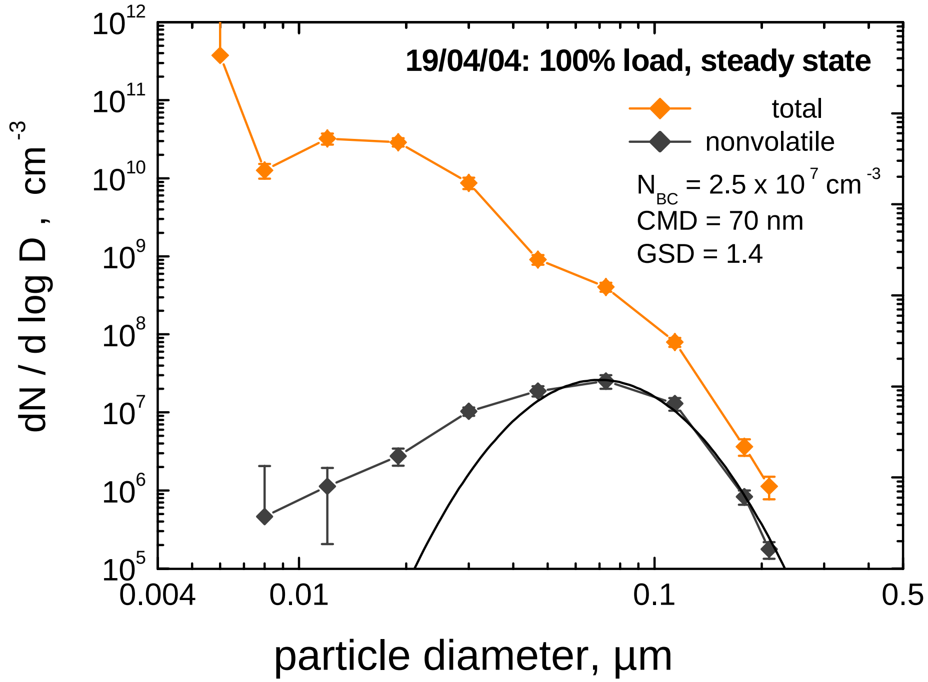


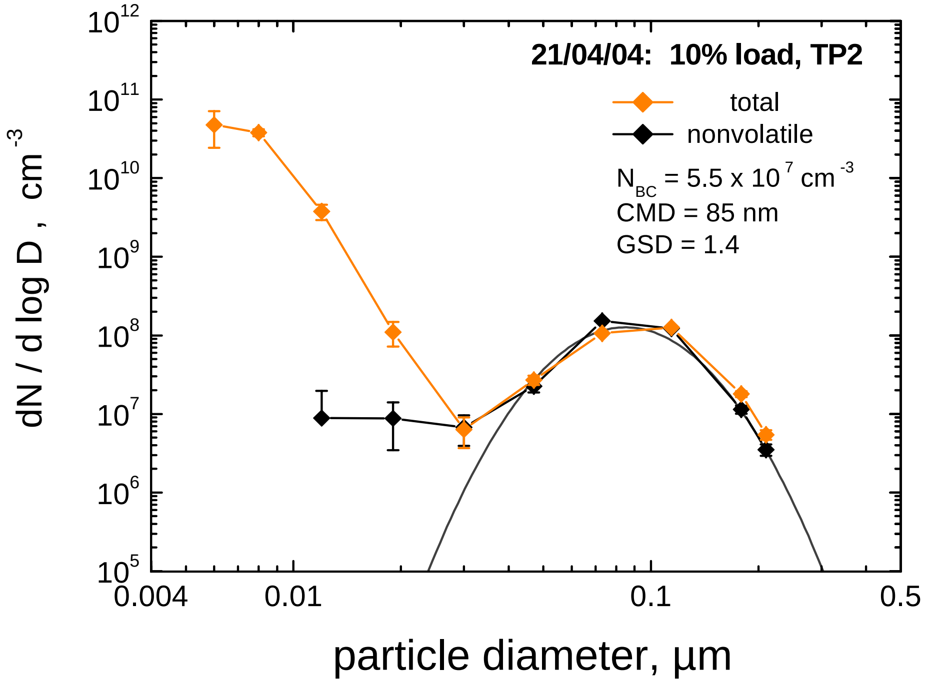
EURO III truck derived marine engine: PM emission and composition

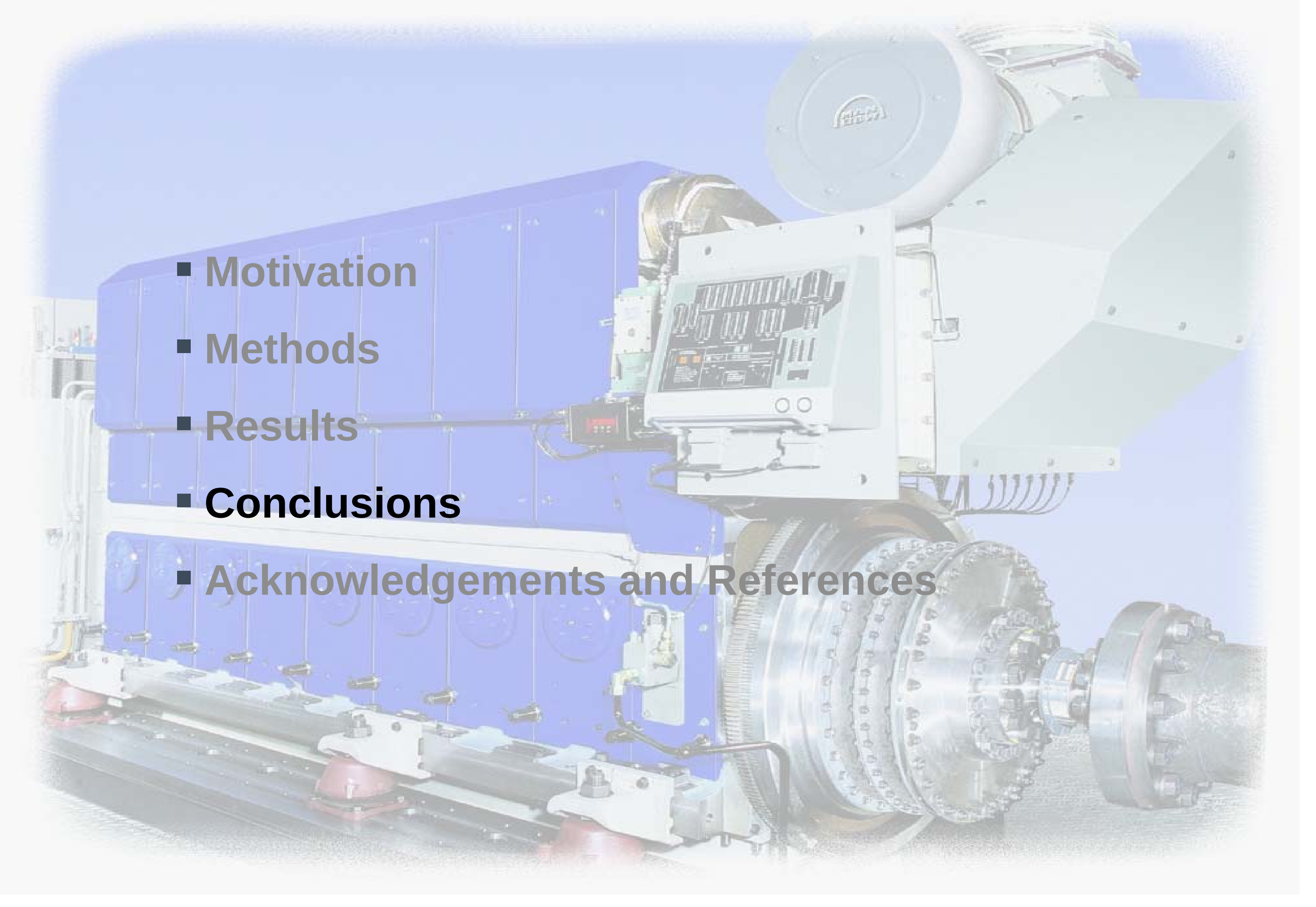


32/40 engine: PM number size distribution

HFO (A)







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Conclusions I

- PM from large four-stroke medium speed Diesel engines for ships consists mainly of volatile material (organic material, sulfates, water)
- PM from vehicle Diesel engines consists mainly of non volatile material (elemental carbon, ash)
- Number size distribution with and without Thermodenuder confirm the large volatile PM fraction of large medium speed marine Diesel engines
- Aitken mode particles at 20 nm consist >99% and accumulation mode particles at 70 nm consist >90% of volatile material at 100% engine load

Conclusions II

- The different fuels show significantly different amounts of sulfates, sulfate bound water and ash, according to the fuel composition
- At high engine loads and for sulfur fuels the sulfates and sulfate bound water dominates the PM emission
- At low engine loads and for low sulfur fuels the organic material dominates the PM emission
- The lower the fuel quality, the higher the absolute PM emissions
- Residual fuels will persist the predominant fuel for ships in the future

Conclusions III

- **Compared to a EURO III truck derived marine engine the elemental carbon emission from large marine Diesel engines for a comparable fuel quality show nearly the same absolute value but the total PM emission is higher due to the higher amount of volatile components**

- **PM for the different investigated large Diesel engines show nearly the same composition characteristics and this is independent of the engine size**

- **Further procedure:**
  Find a conversion efficiency from fuel sulfur to sulfate-particulates

Conclusions VI

Diesel Engines designed for

Petrol Station Diesel	Residual Fuel Oil

Application

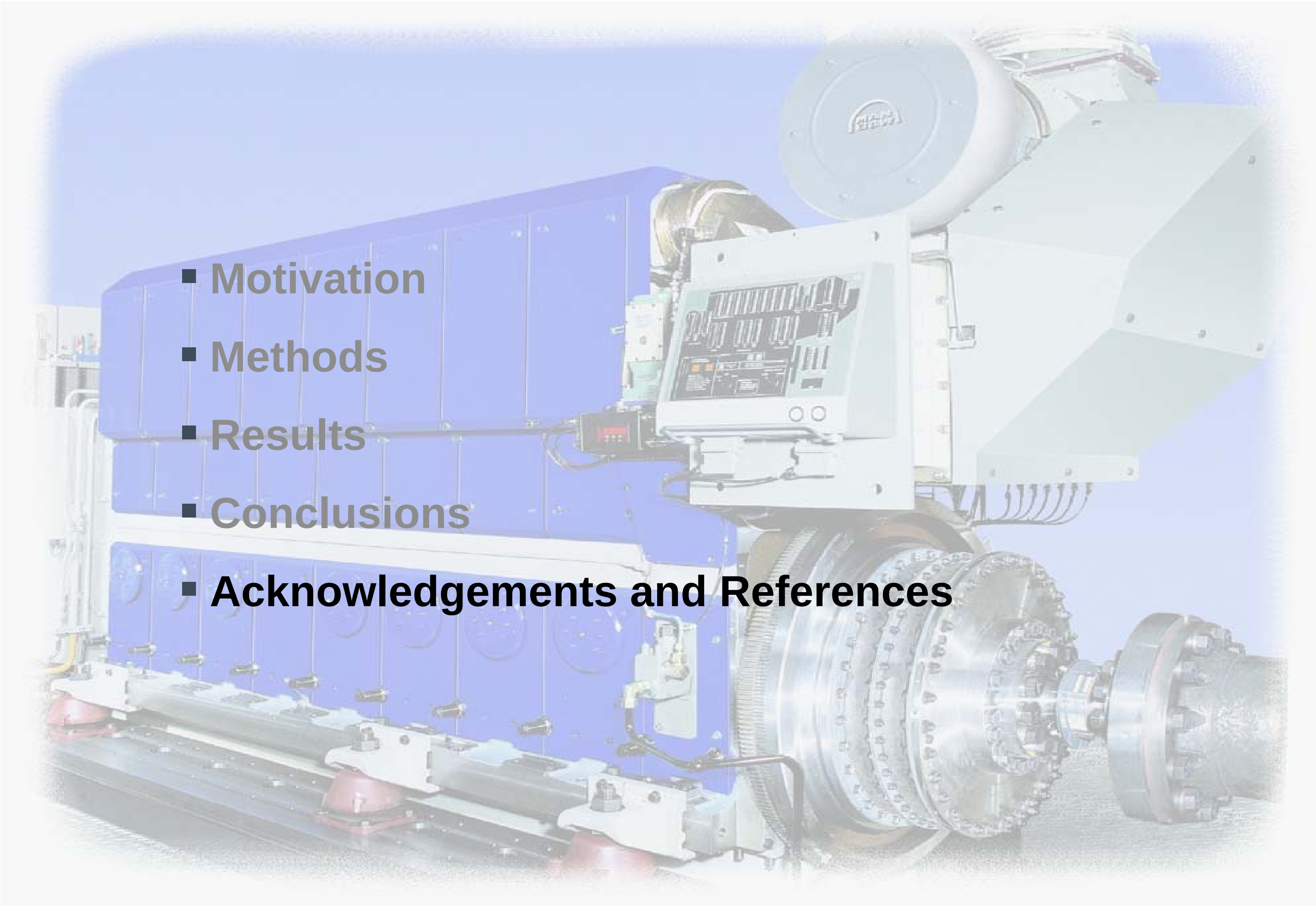
Cars, Trucks, Off-Road	Marine propulsion
Mobile machinery	Stationary Power Plants

Particulate composition

mainly non volatile	mainly volatile

Questions

same effects, limits, measurement procedures?



Acknowledgements and References

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- This work is supported by the EU 6th Framework Program, the integrated project of High-efficiency Engine R&D on Combustion with Ultra-Low Emission for Ships (HERCULES)
- Institut für Physik der Atmosphäre DLR
- Germanischer Lloyd

Reference:

- Det Norske Veritas: Worldwide fuel sulfur distribution, 2004

Thank you very much for your attention!