

# Black Carbon Emissions from Ships

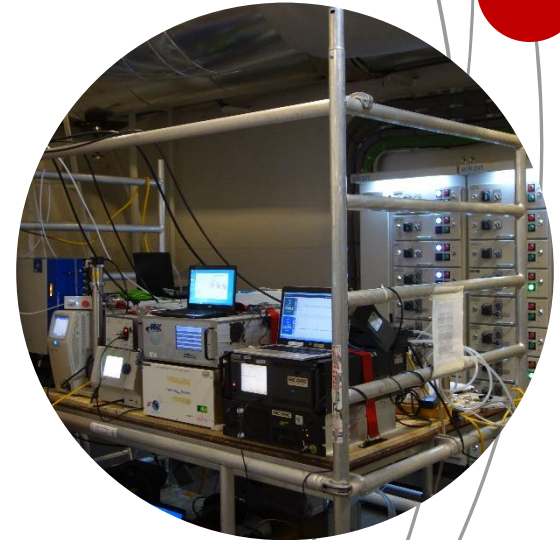
Canada's Research Contribution  
to a Fair Measurement System

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# Outline

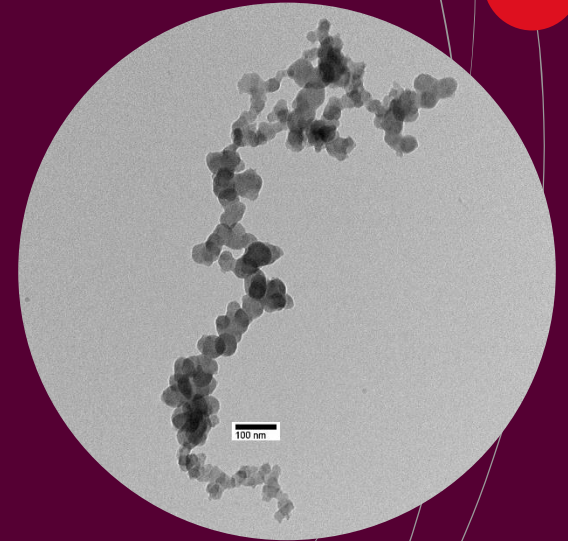
1. **What is Black Carbon? What is it not?**
2. **Black Carbon and Canada at the IMO**
3. **Research for a fair measurement system**
4. **An ISO standard for marine BC measurements: a Canadian perspective**



# WHAT IS BLACK CARBON?

What is it not?

Why does it matter?



# What is Black Carbon (BC)?

**BC is a distinct type of carbonaceous material, formed only in flames during combustion of carbon-based fuels. It has a unique combination of the following physical properties:**

- 1. It strongly absorbs visible light** with a mass absorption cross section of at least  $5 \text{ m}^2\text{g}^{-1}$  at a wavelength of 550 nm;
- 2. It is refractory;** that is, it retains its basic form at very high temperatures, with vaporization temperature near 4000K;
- 3. It is insoluble in water, in organic solvents** including methanol and acetone, and in other components of atmospheric aerosol;
- 4. It exists as an aggregate of small carbon spherules.**

# What is Black Carbon (BC)?

*[...] formed only in flames during combustion of carbon-based fuels [...]*

**In some flames, BC is fully oxidized and broken into oxidation products (CO<sub>2</sub> and CO).**

**In an engine cylinder**

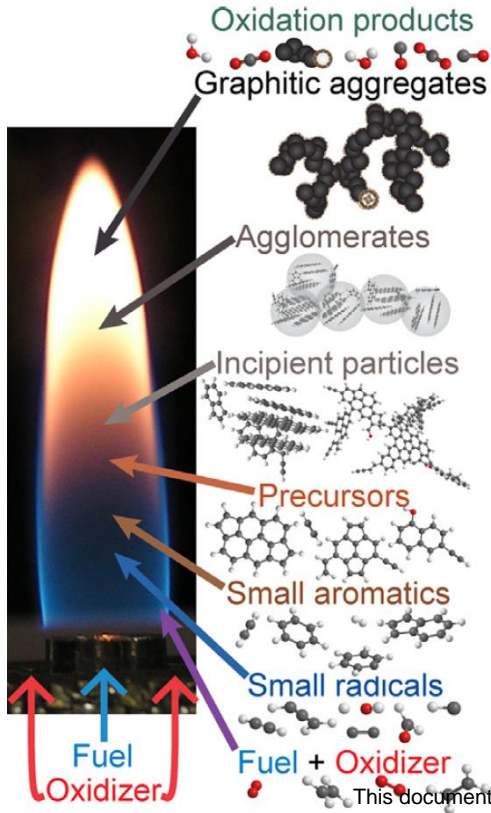
**Mixing with OXYGEN**

**AND**

**TIME**

**are limited.**

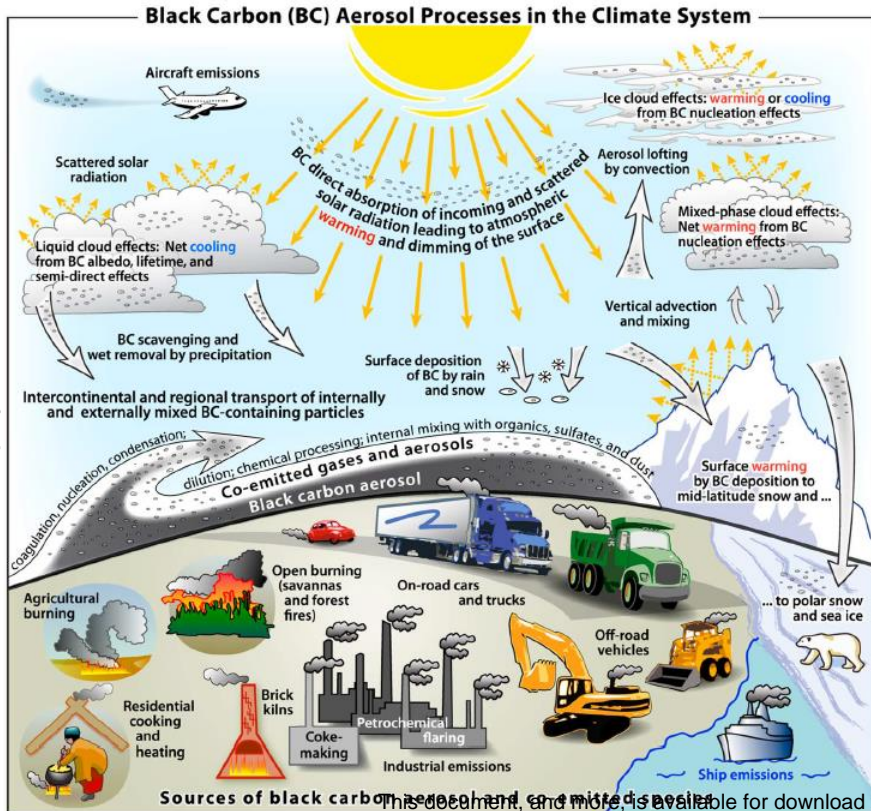
**BC is emitted when oxidation is incomplete.**



# What is Black Carbon not?

- **BC is a fraction of Particulate Matter (PM) and is non-volatile**
  - It is not related to the sulphur content in the fuel
  - It does not condense as the temperature drops
  - It is not destroyed by atmospheric photochemistry
- **Not brown carbon**
  - Not all of the light-absorbing fraction of PM
  - It is not equivalent to smoke or FSN
- **Not ash or metals**

# Black Carbon and the climate



Short-lived climate pollutant  
**Atmospheric lifetime:**  
 ~ weeks

**2<sup>nd</sup> largest climate forcer (after CO<sub>2</sub>)**

**Lifetime once deposited on snow: much longer**

# Health effects of Black Carbon

- **Association of BC and all-cause and cardiovascular mortality, and cardiopulmonary hospital admissions.**
- **Association of health effects with BC are 4 to 9 times stronger than with PM<sub>2.5</sub>**
- **BC thought to be a carrier for other toxic airborne particulate constituents into organs and blood stream**
- **An unintentional experiment on people in China lead to a 5.5 years decreased in life expectancy linked to BC.**
- **Health related costs in Canada alone: ~\$5B/yr**

See, for example: WHO, 2012; Janssen et al., EHP, 2011;  
US EPA, 2011; Chen et al., PNAS, 2013; Env. Canada, 2013

This document, and more, is available for download from Martin's Marine Engineering Page - [www.dieselduck.net](http://www.dieselduck.net)



# CANADA AT THE IMO

A Leader in Black Carbon Research



# A leader on the Black Carbon file

- **2016 (PPR3): Canada involved in 3 of 6 BC papers**
  - Gathered consensus on BC definition
- **2017 (PPR4): Canada involved in 3 of 10 BC papers**
  - Coordinated correspondence group on reporting protocol
- **2018 (PPR5): Canada involved in 6 of 15 BC papers**
  - Gathered consensus on appropriate BC instruments (with guidance)
  - Coordinated correspondence group on control measures
- **2019 (PPR6): Canada involved in 7 of 11 BC papers**
  - Gathered consensus on closing the remit (with guidance)

# Research & Scientific Contributions

- **Promoted the scientific definition of Black Carbon**  
A material with distinctive climate and health properties, and distinctive optical, physical and chemical properties
- **Contributed 4+ studies comparing measurement instruments**  
Selected multiple: FSN, PAS, LII
- **Contributed 3+ studies evaluating BC control measures** (not discussed)  
EGR, SCR, EGC and different fuels (LNG, diesel, Blends, HFO, etc.)
- **Suggested that a standard, traceable measurement method is needed**

# RESEARCH FOR A FAIR MEASUREMENT SYSTEM

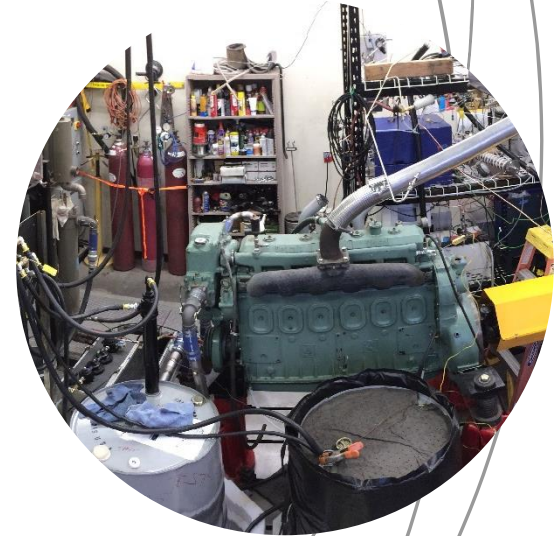
The research that supports IMO participation



# Sample conditioning and calibration

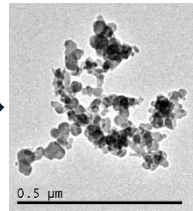
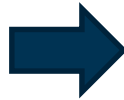
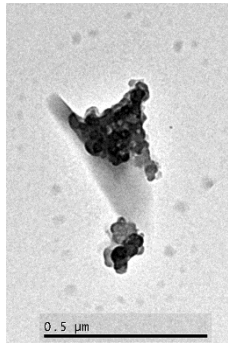
Calibrating the instruments with a common source (as in aviation) contributed to consistency among instrument responses.

Sample conditioning (catalytic stripping + sulphur adsorbers): 1) improved results on a qualitative level, 2) improved results on a quantitative level only after calibration, producing a modest impact

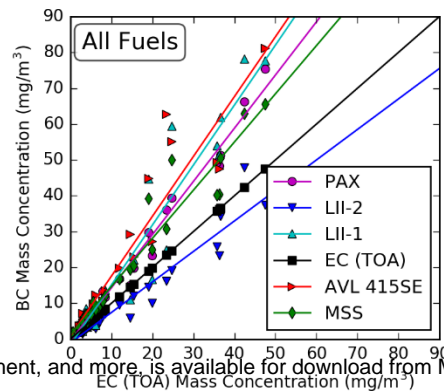
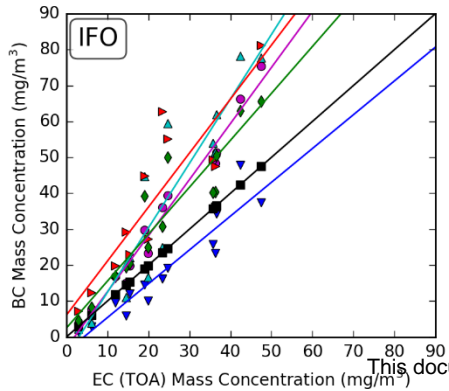
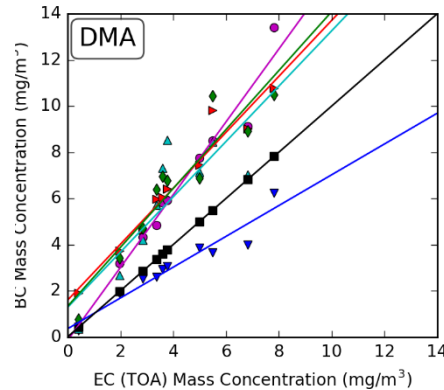
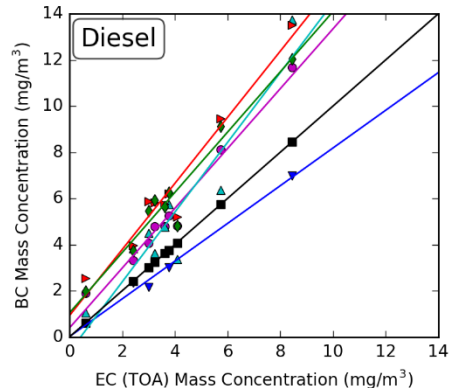


7 instruments based on different measurement principles:  
FSN, LII, MSS, TOA (lab & field), MAAP & Aethalometer.

PPR 3, Canada,  
Presentation, Feb 2016



# BC measurement instrument linear response



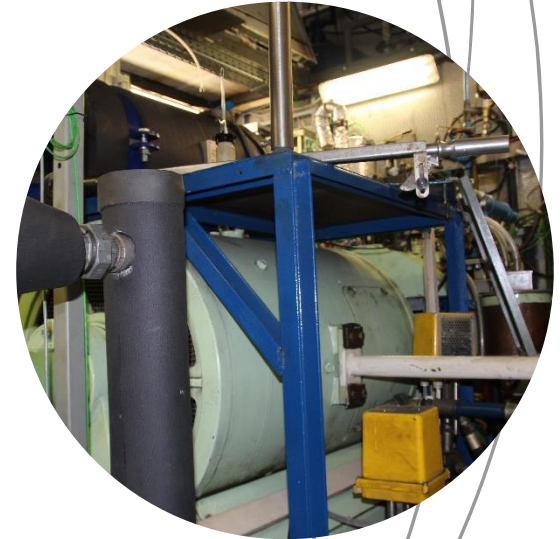
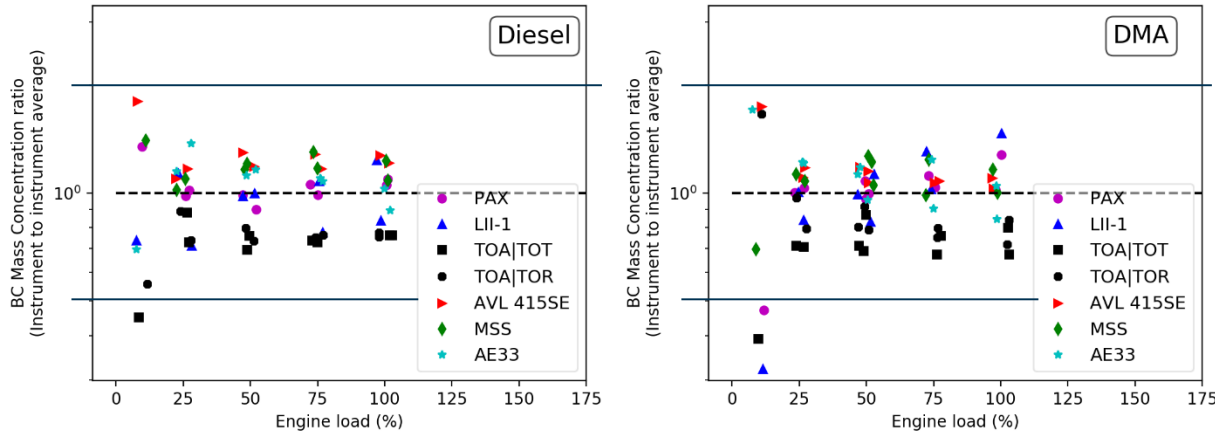
**Rostock test engine:**

**Linear response between the instruments for all fuel.**

**Best correlation with diesel ( $R^2 = 0.97$ ), still good with IFO ( $R^2 = 0.94$ ). (PPR 5/INF.10)**

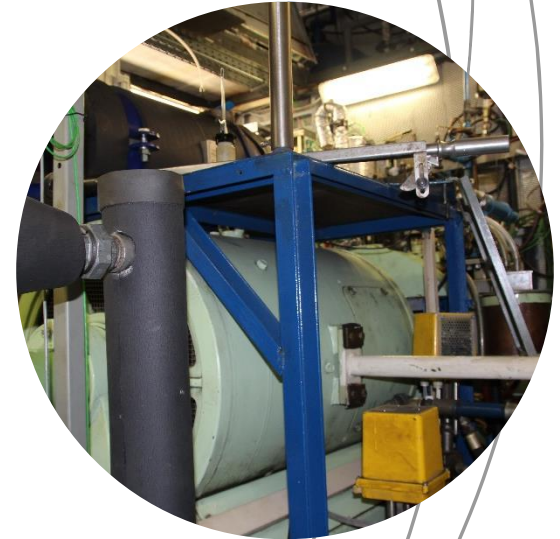
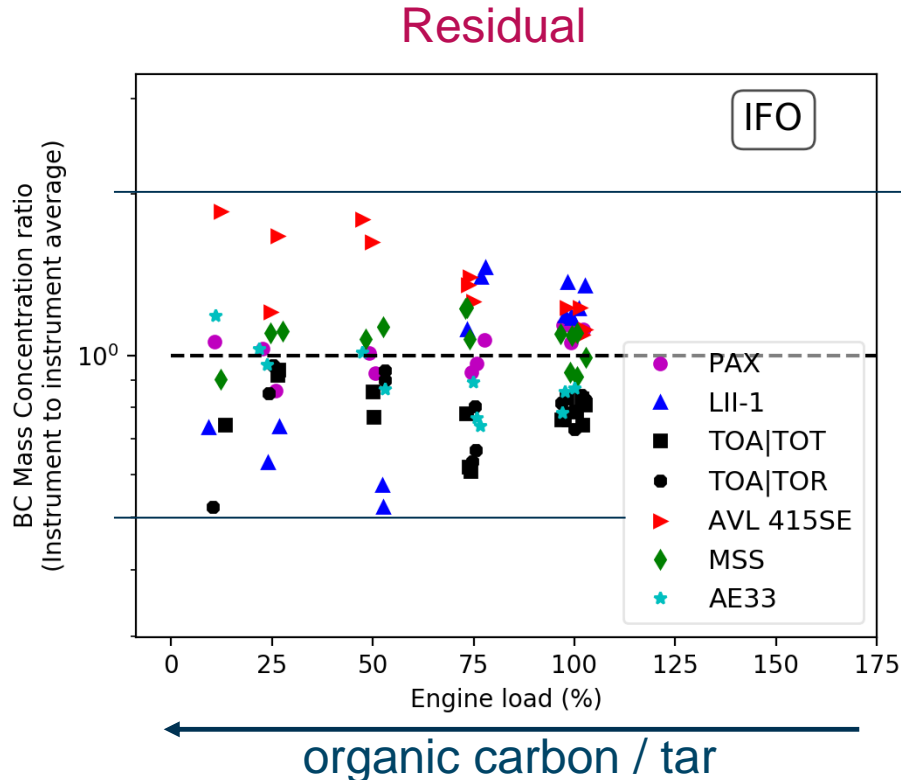
# But do they really agree?

## Distillates



- Reasonable agreement between instruments.
- More scatter at the lowest load when there is more organic interference
- TOA generally lower than other instruments

# But do they really agree?





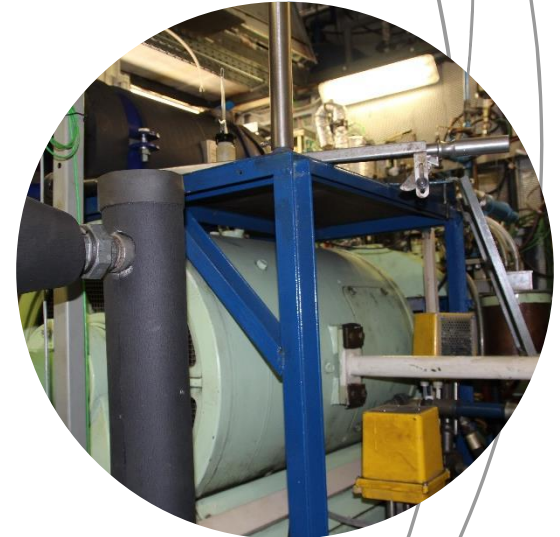
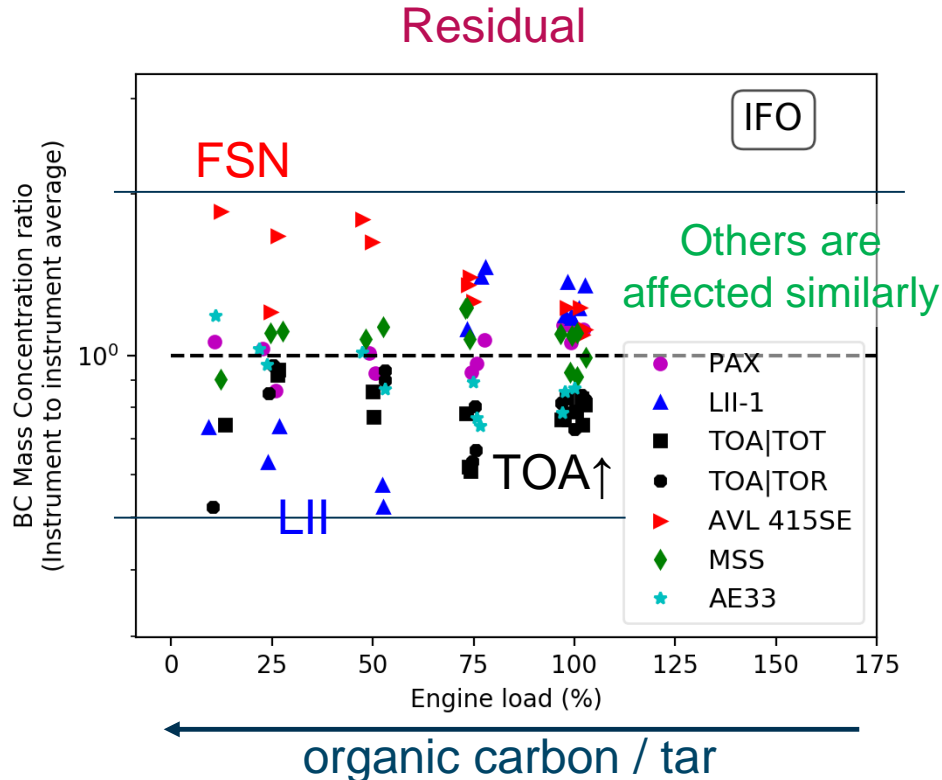
# What's so special with residuals?

	Soot BC	Char BC	Tar brC	Soluble brC
<b>Solubility<sup>a</sup></b>	Negligible solubility in common solvents			Soluble
<b>Light absorption</b>	300–1000 nm [detected as eBC]			300–600 nm
<b>Chemical state</b>	Contorted graphene layers		Amorphous	Distinct molecules
<b>Carbon bonding</b>	sp <sup>2</sup> dominated		sp <sup>2</sup> and sp <sup>3</sup>	sp <sup>2</sup> and sp <sup>3</sup>
<b>Vapourization at<sup>b</sup></b>	~ 4000 K [EC, rBC]		~ 1000 K [EC]	< 600 K
<b>Produced by</b>	Flame synthesis	Fuel-droplet pyrolysis	Partial pyrolysis	Oxidation, pyrolysis, ...
<b>Morphology</b>	Aggregated spherules	Porous cenospheres [...]	Spheres	Spheres or coatings

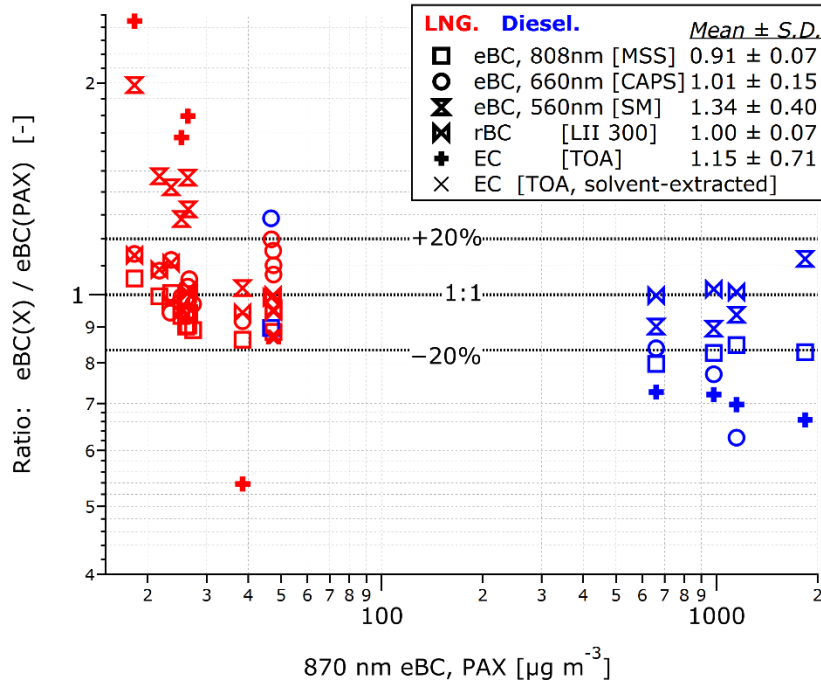
HFO



# What's so special with residuals?



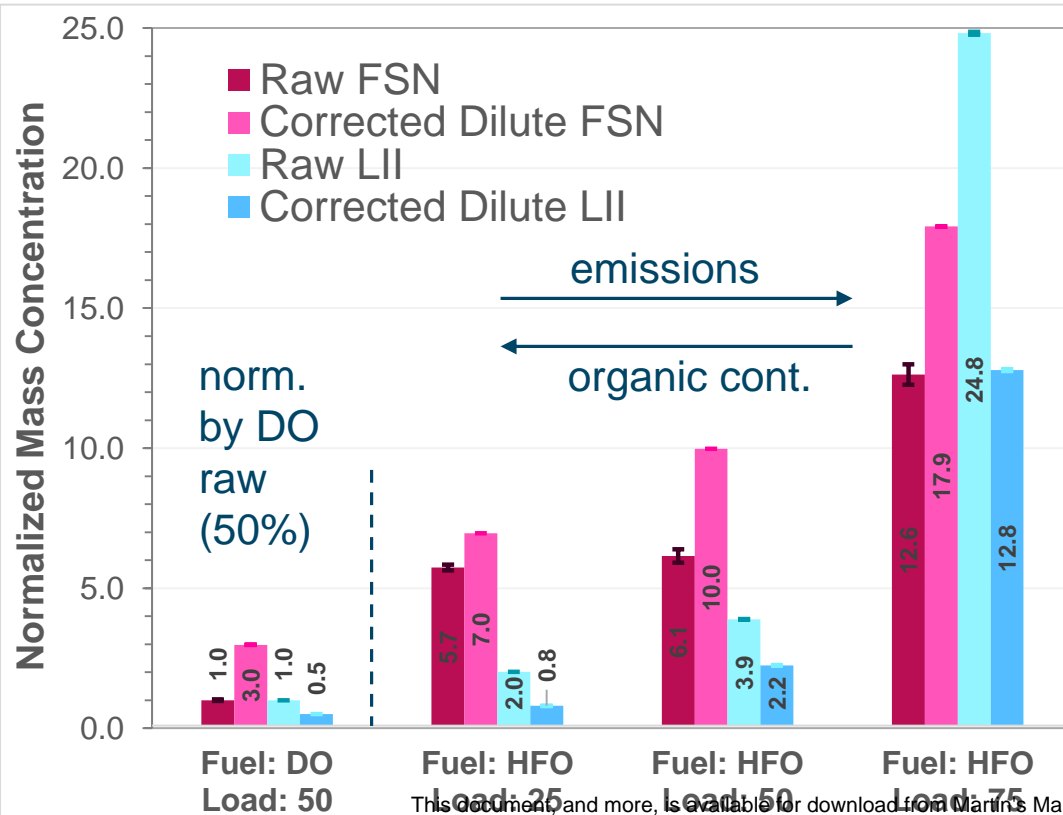
# Low BC measurements (case: NG)



Special considerations also go into measuring very low concentrations, very humid exhaust or organic-rich emissions.

- IMO-selected FSN (SM in Figure) overestimates at low concentration (even above LOD)
- Conventional TOA becomes inaccurate with high organic content

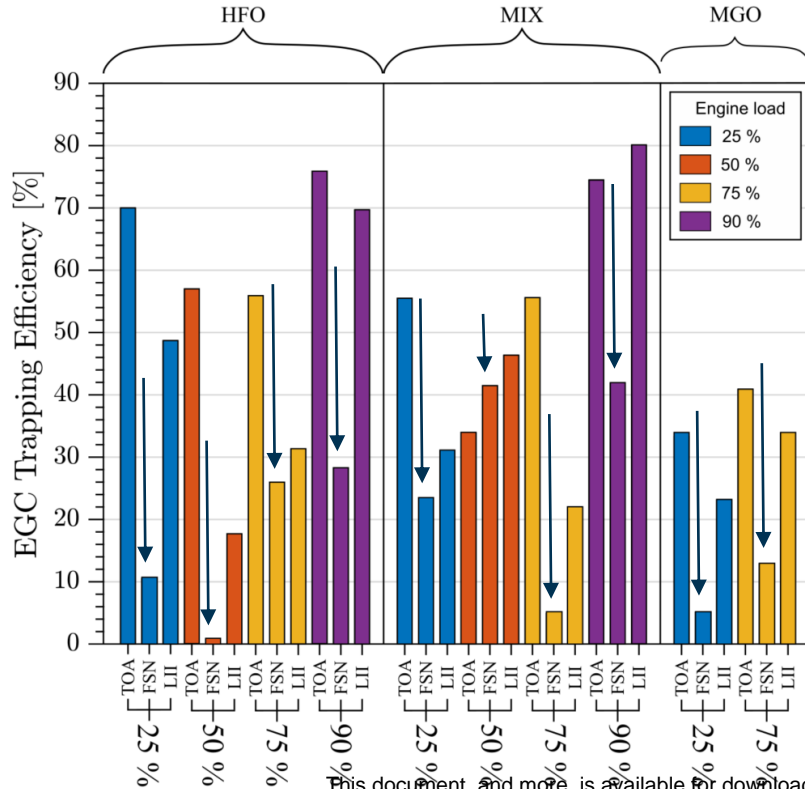
# Measurement methods matter



## Testing the effect of ISO 8178 dilution and condensation on BC measurements with LII & FSN

- LII measures half the concentration after dilution
- FSN always sees more after dilution: biased by organic condensation
- Undiluted FSN is also biased by organic condensation

# Measurement methods matter



**Exhaust Gas Cleaning = Scrubber**

**The FSN requires conditioning when organic material condenses**

$$\text{Trapping efficiency} = \frac{[BC]_1 - [BC]_2}{[BC]_1}$$

**$[BC]_1$  is a little overestimated**

**$[BC]_2$  is very overestimated**

**$[BC]_1 - [BC]_2$  is underestimated**

**Solution: sample conditioning to remove organics**

# AN ISO STANDARD FOR MARINE BC MEASUREMENTS

*A Canadian Perspective*



# Developing a fair measurement system for Canadians

- **ISO/TC 70/SC8 (Exhaust gas emission measurement) develops and reviews ISO 8178 (and ISO 11614)**
- **To influence the development of a standardized BC measurement system at ISO, Canadians must form a Mirror Committee**
- **A Mirror Committee must have a minimum of 5 Canadian stakeholders willing to review the proposed standards**
- **Stakeholders can be from 1) industry/commerce, 2) government/AHJ, 3) consumer/public interest, 4) labour/unions 5) academic/research bodies, 6) standards application/dev org., 7) NGOs**

# Developing a fair measurement system for Canadians

**Canadian Mirror Committees can bring value for Canada in some of the following categories:**

- 1) Trade benefits**
- 2) Advancement of the national economy**
- 3) Assisting consumers**
- 4) Benefiting the health, safety, and welfare of workers and the public**
- 5) Supporting sustainable development**
- 6) Support to government**



# Developing a fair measurement system for Canadians

## Mirror Committee members:

- review, comment, vote on work items
- ensure the Canadian perspective is taken into account
- have a privileged influence on the work item proposal by Canada (to develop a measurement method for BC)

**Small time commitment, great potential for benefits to Canadians and the world**

**Interested? [stephanie.gagne@nrc-cnrc.gc.ca](mailto:stephanie.gagne@nrc-cnrc.gc.ca)**

# Thanks to our collaborators

**University of California Riverside (USA)**

**Marena Ltd and University of Rostock (Germany)**

**MAN Energy Solutions (Denmark)**

**Alfa Laval Aalborg (Denmark)**

**University of British Columbia (Canada)**

**Test ship: Seaspan Ferries (Canada)**

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# THANK YOU

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