Marine Black Carbon Emissions Testing Test Plan and Approach

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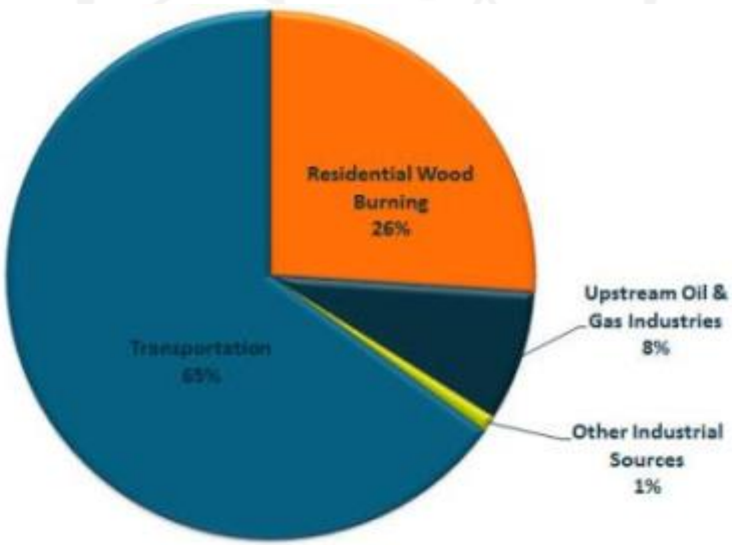
Presentation Outline

- Background
- Objectives
- Research Team
- Research Approach
  - Laboratory bench testing
  - Ocean testing
- Parallel efforts
  - California Air Resources Board
  - Carnival

Background-Policy

- Marine traffic and related port activities contribute to air pollution in many cities, ports and along inland waterways.
- The allowable sulphur level for marine fuels in Canada in some cases can reach 1000 mg/kg*.
- Canada's 2013 National Pollutant Release Inventory (NPRI) shows that marine transportation contributes 89% of the total mobile SO_2 emissions#.

- According to the first Canadian Black Carbon (BC) Inventory released in 2013†, a 65% of the total 45,000 tonnes of BC emitted in Canada was attributed to the transportation sector.
- Marine BC emissions was 1600 tonnes in 2013 compared to the total 29,000 tonnes of BC from all mobile sources.



2013 BC emissions in Canada

* https://www.ec.gc.ca/energie-energy/default.asp?lang=En&n=7A8F92ED-1

\# http://www.ec.gc.ca/inrp-npri/donnees-data/ap/index.cfm?lang=En

† http://ec.gc.ca/pollution/default.asp?lang=En&n=3F796B41-1&offset=3&toc=show

Drivers for on-board / real world marine emissions measurements

- Real world measurement and analysis of exhaust emissions from various off-road equipment including marine is done to support:
  - Development of regulations, emissions factors, and inventories
  - Method development for sampling and analysis
  - Evaluation of emissions control technologies and strategies such as cleaner fuels

Emerging issues for Marine Sector

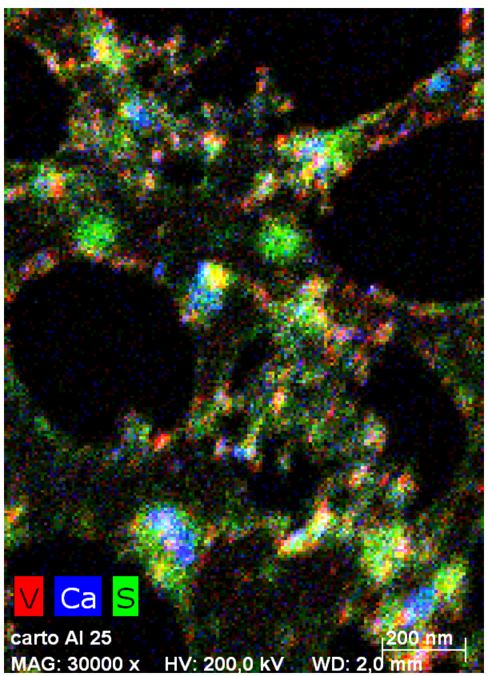
- Emissions control and reduction targets for various competing transportation modes
- Generic emissions factors typically used; not specific to engine age or technology, fuel quality, engine operation parameters, etc.
- Changing emissions profiles resulting from new exhaust emissions control strategies and technologies

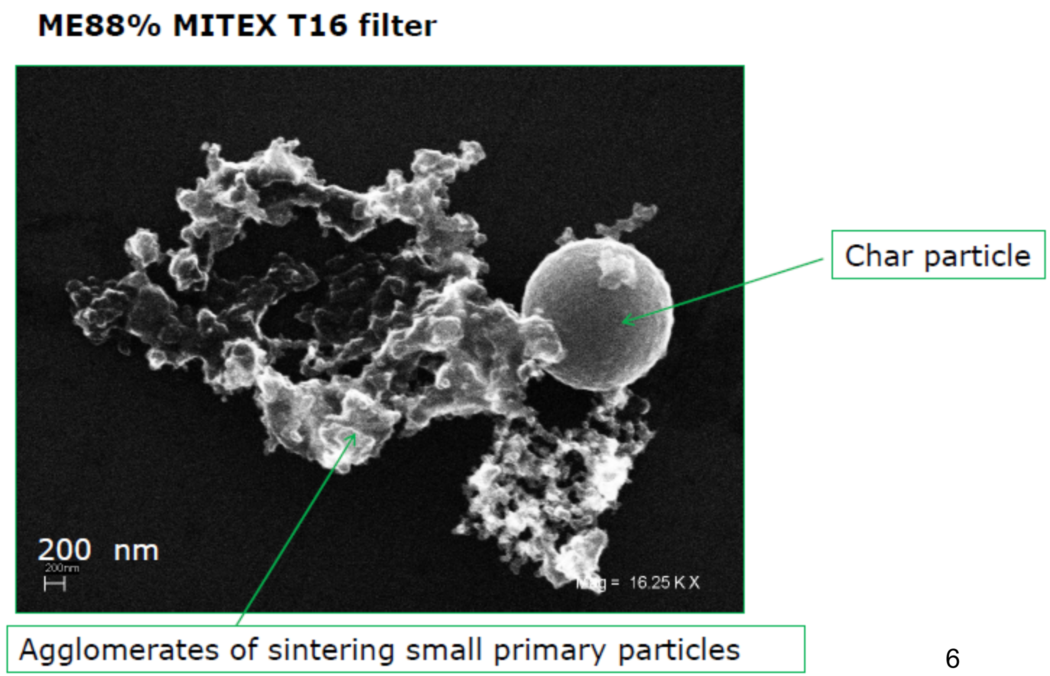
Background-Technical

- BC EF quantification practices not well understood with the different fuels, loads, engines, and measurement methods, thus making BC mitigation difficult

- Reported BC EF vary by a factor of 10

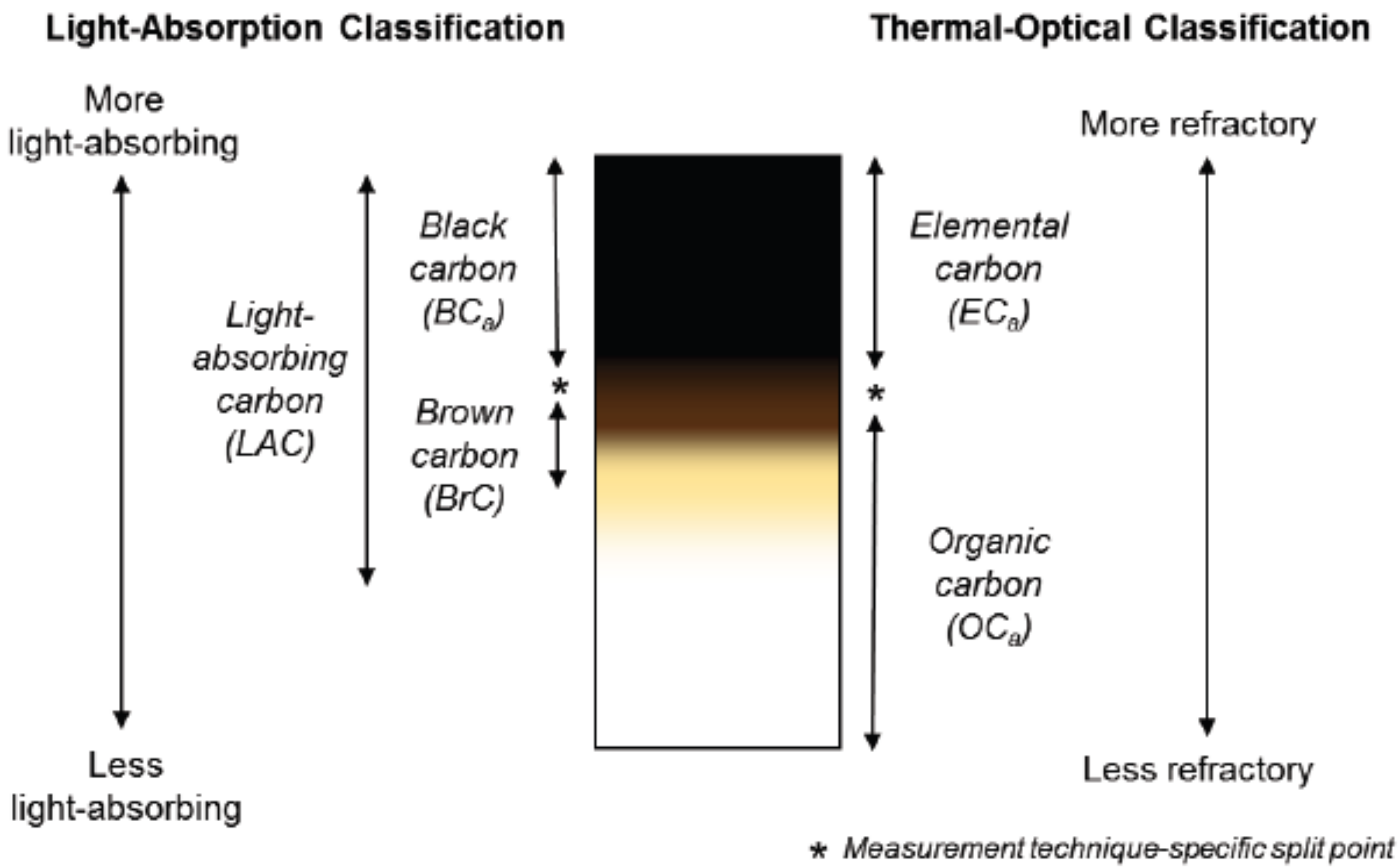
PM Also Varies by Sampling Approaches





Source: Moldanova et al ICCT 2014 workshop

Why is BC Characterization Difficult



Source: EPA

Objectives

- Controlled laboratory testing (engine test stand)
  - Evaluate numerous BC instruments
  - Vary engine load and fuel
  - Identify recommended practices
- Evaluate recommended practices on OGV

Engine Laboratory Test Stand

Engine Description			
Detroit Diesel 6-71N (naturally aspirated)	4 valves per cylinder	210 hp	High speed (2100 rpm)
2-stroke design with uniflow scavenging	0.348 lb/bhp-hr	7.0 L Disp.	18.7:1 Compression Ratio mechanically controlled

- The DDC 71 series diesel engine was very popular in marine propulsion
- Valley Power Systems was contracted to operate this engine on HFO for the Navy
- Current status

Engine Test Stand Conditions

Fuel [2]	Load (ISO E-3)	Repeats	Instruments [1]
MGO <0.1 S	**Load**: 100, 75, 50, 25, and 10% (VSR) **Speed**: 100, 91, 80, 63, and 45% (VSR)	3	Table 3-2, 3-3, and 3-4
HFO high S	**Load**: 100, 75, 50, 25, and 10% (VSR) **Speed**: 100, 91, 80, 63, and 45% (VSR)	3	Table 3-2, 3-3, and 3-4
HFO <0.1 S	**Load**: 100, 75, 50, 25, and 10% (VSR) **Speed**: 100, 91, 80, 63, and 45% (VSR)	3	Table 3-2, 3-3, and 3-4

[1] Additionally UCR plans to measure the criteria pollutants (CO, NOx, SO2,), total hydrocarbons and CO2 following methods outlined in 8178-1/-2. The main purpose of these measurements is to ensure that the engine operation is representative of a well maintained engine. The Team will report any changes in the measured gases.

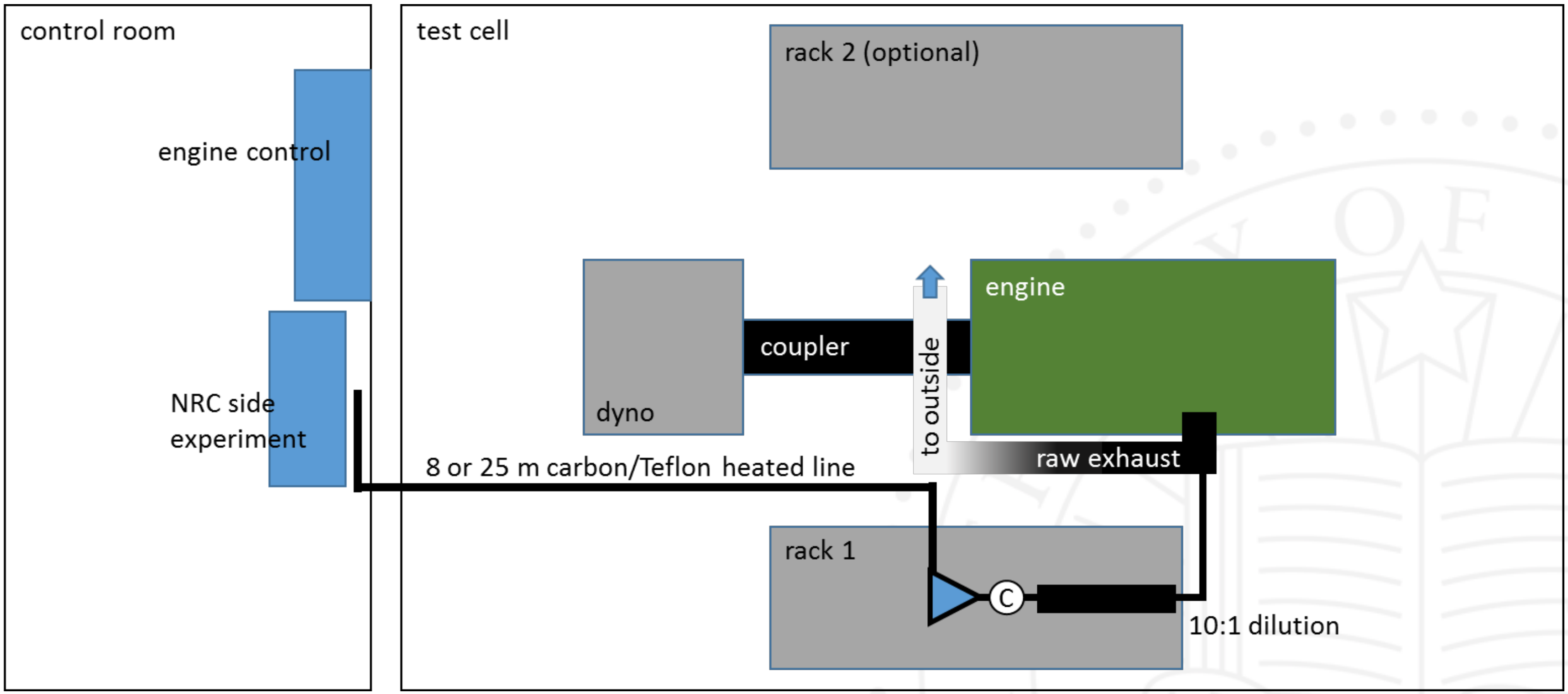
[1] If additional fuels are available for testing and additional dollars are allocated the testing matrix can easily be expanded to consider these other fuels.

Engine Dynamometer Test Stand

UC Riverside's Engine Dynamometer (15 years of experience)

1) Up to 600 hp
2) Repeatability ~ 1% (torque/ Hp)
3) Transient and steady state
4) Fuel control (temperature and pressure)
5) Intake air control (humidity and temperature)
6) Cooling water control
7) Room ventilation control

Engine Test Stand Proposed Layout

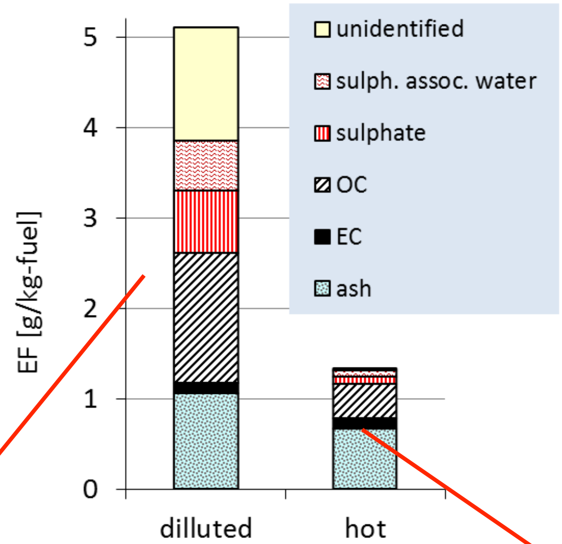


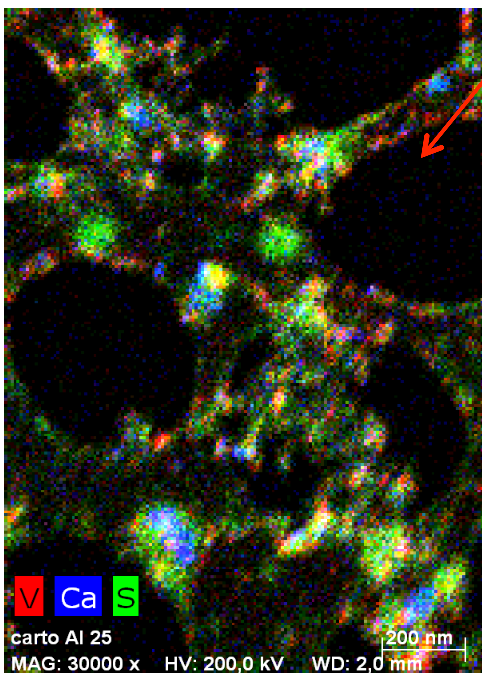
Source: NRC

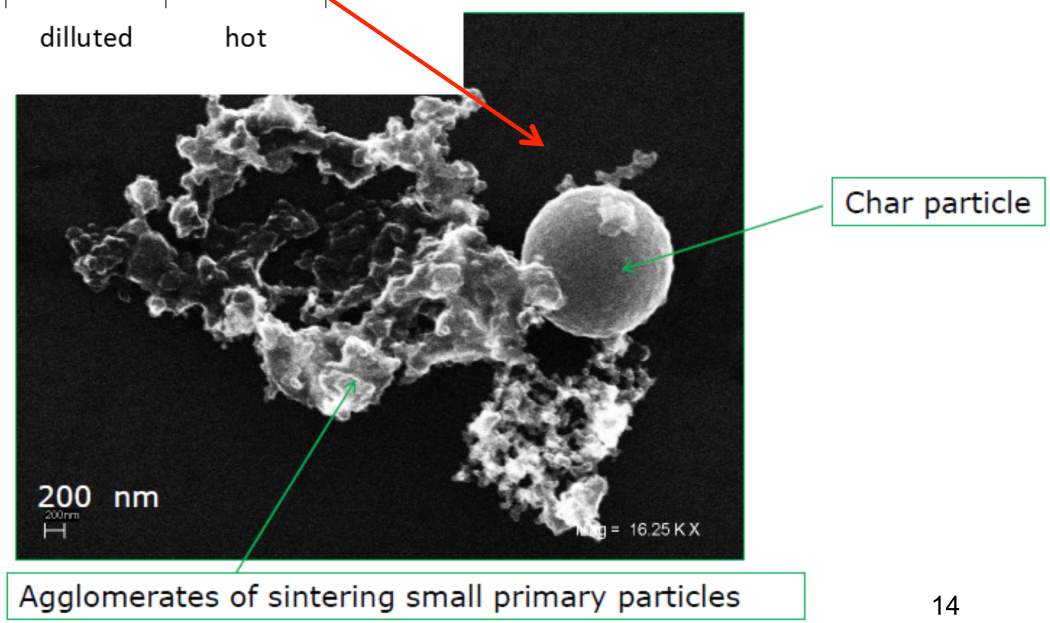
Sampling Approach

- Dilution: three main sample branches
  - No dilution (raw sampling)
  - Traditional IMO type stack sampling ~ 10:1
  - High dilution (simulated plume sampling) > 100:1
- Sample conditioning
  - Best recommended practices
- Calibration (CAST)

Selecting the Correct Dilution is Important







Source: Moldanova et al ICCT 2014 workshop

Expected Test Stand PM Concentrations

(HFO 3% Sulfur Fuel)

PM (ug/m^3)	Dilution ratio			
Species	1 : 1	10 : 1	300 : 1	1000 : 1
total PM	5,656	12,000	480.0	144.0
organics	656	4,800	192.0	57.6
sulfate	0	6,600	264.0	79.2
elemental	5,000	500	16.7	5.0
ash other	100	10	0.3	0.1

Engine Test Stand Measurements

Raw dilution samplers (1:1)

AVL 415SE Smoke Meter from the raw exhaust	**Filter-type smoke meter (ISO 10054) from raw exhaust in-kind contribution AVL see Attachment E for letter.**
(Optional) **Laser Induced Incandescence (LII)**	(Optional) **PM mass collected on Teflon filter.**
(Optional) **Elemental & organic carbon on quartz filter analyzed by NIOSH & IMPROVE methods (Sunset instrument)**	(Optional) **GC by GC Mass Spectroscopy**

Engine Test Stand Measurements

ISO dilution samplers (~10:1)

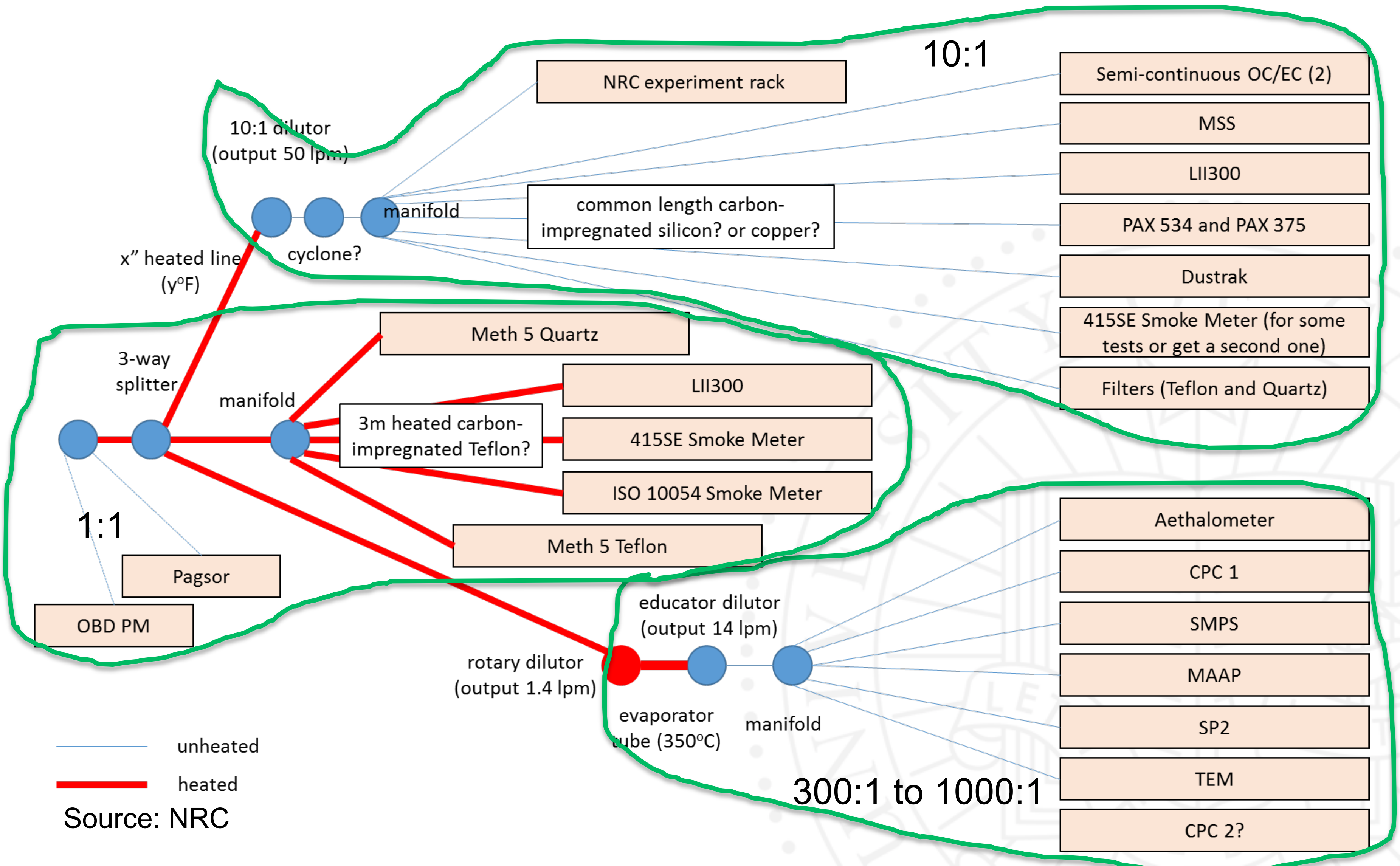
AVL Micro soot sensor (MSS) 870 nm wavelength	**Elemental & organic carbon on quartz filter analyzed by NIOSH & IMPROVE methods (Sunset instrument)**
Laser Induced Incandescence (LII)	**PM mass collected on Teflon filter.**
(Optional) AVL 415SE Smoke Meter from the raw exhaust	**(Optional) GC by GC Mass Spectroscopy**
Droplet Measurement Technologies (PAX) PA system, in-kind contribution DMT, see Attachment E for letter.	**DMT PAX PA system 375 nm wavelength**

Engine Test Stand Measurements

High dilution samplers (~300:1 up to 1000:1)

Aethalometer AE33	**Multi-angle absorption photometer (MAAP)**	**CPC-Catalytic Stripper (CPC-CS)**
Condensation particle counter (CPC)	**Single Particle Soot Photometer (SP2)**	**Aerosol Particle Mass Analyzer APM-SMPS**
Particle size distribution with (SMPS)	**Transmission Electron Microscopy (TEM)**	**Aerosol Mass Spectrometer (AMS)**
(Optional) GC by GC Mass Spectroscopy		

Proposed Engine Test Stand Arrangement



Source: NRC

Possible Duplicate Measurements Between Dilution Probes

- All (1:1, 10:1, and 300:1)
  - GC by GC MS
  - LLI
- 1:1 and 10:1
  - Smoke meter?
  - Teflon PM mass
  - EC/OC
- 10:1 and 300:1
  - PA 820 nm
  - PAX 375 nm
  - PAX 534 nm?

Comprehensive Team

Team Member	Expertise
From UCR: Drs. Johnson & Miller plus Professors Cocker, Jung, and Bahreini;	• Measurement and analysis of marine air emissions • Familiarity with BC instrumentation approaches and sampling • Experience with bench testing of emissions from marine engines • Experience with on-board vessel emissions testing
From Environment Canada: Scientific members from Dr. Tak Chan group	• Measurement and analysis of marine air emissions • Familiarity with BC instrumentation approaches and sampling • Experience with bench testing of emissions from marine engines • Experience with on-board vessel emissions testing
Dr. John Koupal of Eastern Research Group (ERG)	Familiarity with marine inventory development, including emission factor analysis, vessel population, and activity patterns.
Dr. Miller of UCR	Has proven relationships within the industry and demonstrated ability to access vessels for testing.
Professor Lynn Russell of UC San Diego	• Familiarity with BC instrumentation approaches and sampling • Expert on marine aerosol and SP2 method
From National Resource Canada (NRC), Dr. Kevin Thomson	• Measurement and analysis of marine air emissions • Familiarity with BC instrumentation approaches and sampling • Experience with bench testing of emissions from marine engines • Experience with on-board vessel emissions testing
AVL/Sun Set Laboratories	Familiarity with BC instrumentation approaches, sampling and access to new instruments

Ocean Going Vessel Testing

- Recommend a BC EF:
  - Measurement method
  - Sampling conditioning method

- Evaluate recommendations on various in-use vessels
  - Fuel switching
  - Controls (Scrubbers and Flow through filters)
  - Various loads (as permitted)

Ocean Going Vessels Proposed

Vessel Name	Vessel Type	Engine	PM Control	Contract
Tarago	RORO	Maine: MAN B&W 21 Mw	Pre/Post Scrubber	ICCT
Tarago	RORO	AE: MAN B&W 1MW	Pre/Post Scrubber	ICCT
tbd	tbd	tbd	tbd	ICCT?
tbd	tbd	tbd	tbd	ARB (up to 3)
Carnival	Cruise Line	Wartsila and MAK 8-12 Mw (multiple)	Pre/Post PM Scrubber and Filter	Carnival (up to 7)

- The Tarago is a vessel that has both main and AE engines for a range of conditions in one setup. Possible fuel changes also.

Proposed Carnival BC Testing

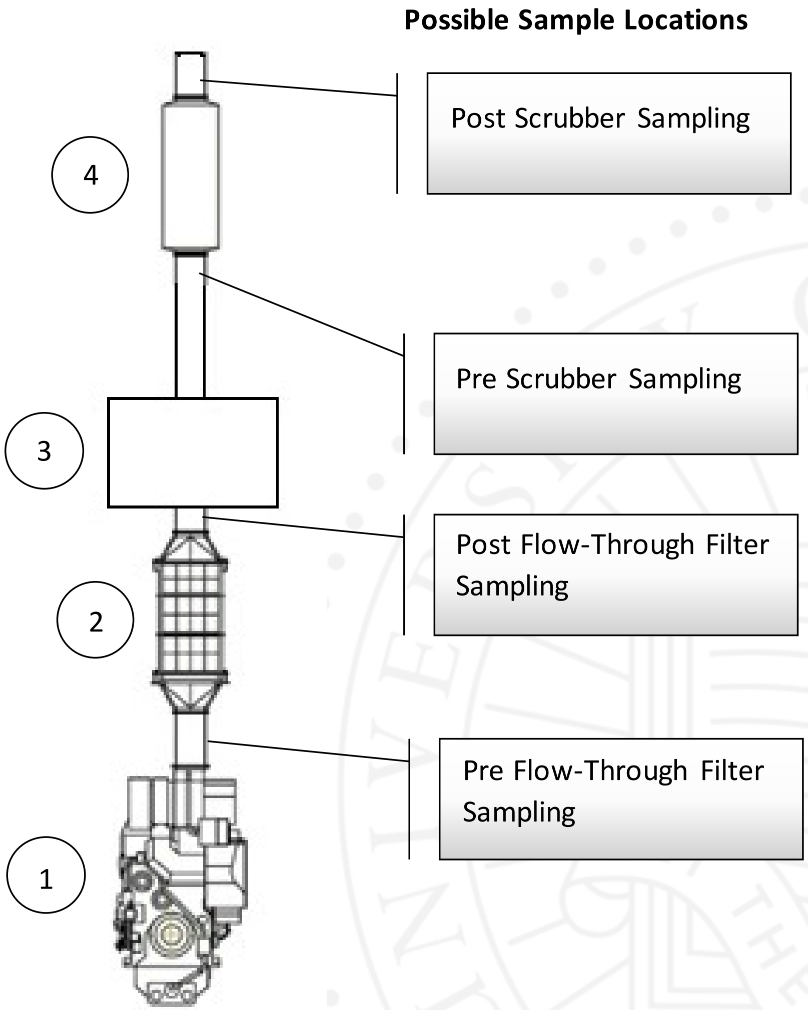
Main Components Exhaust Gas Cleaning System

1: Engine

2: Flow-Through Filter

3: Economizer

4: Exhaust Gas Scrubber



Project Expectations

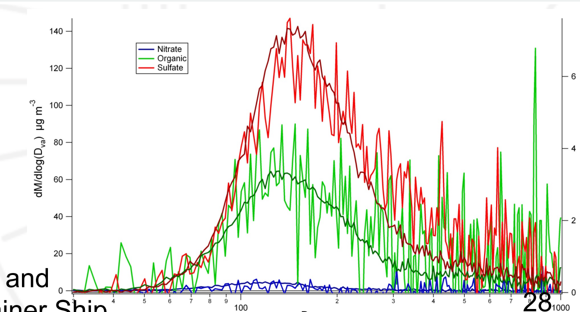
- Comprehensive characterization of laboratory PM from marine engines on marine fuels
- Evaluation and quantification of BC EF measurement methods
  - Instruments
  - Sample conditioning
  - Calibration
- On-vessel demonstration of these methods for validation

Questions

Backup

Ocean Going Vessels and Craft Testing Experience

Vessel Type	Engine	Test Count	Motivation
Container Class (10), Tankers (1), and Roll On Roll Off (1)	Main/Aux	12	Fuel switching, NO_x control (SCR aux), PM control (scrubber aux), fuel switching, reduced speed.
Ferry, Shuttles, Tugs, Dredgers, Hybrid Tug	Main/Aux	10	Fuels (bio), NOx control (SCR), Clean tech's, hybrids.

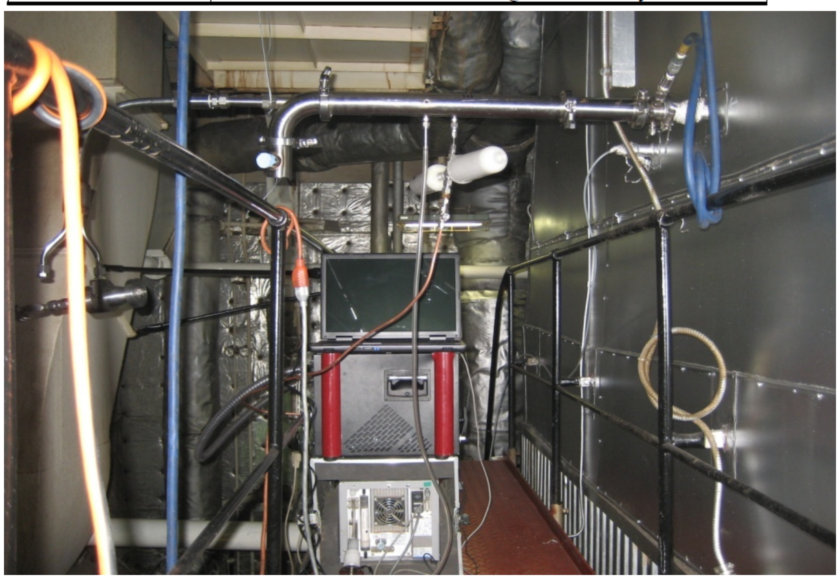


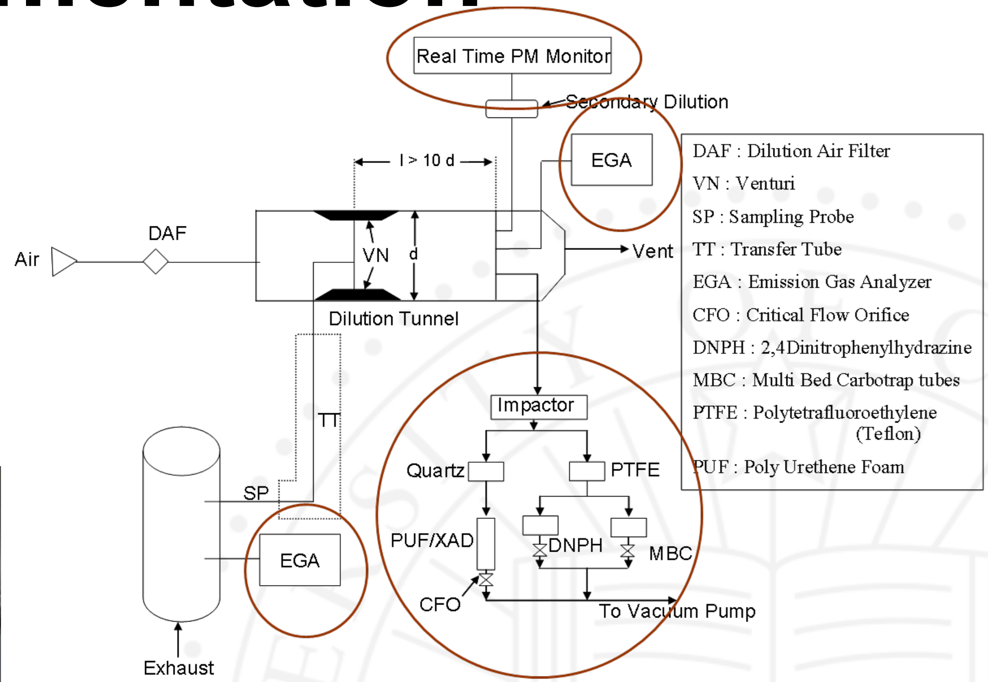
Murphy S., et al "Comprehensive Simultaneous Shipboard and airborne Characterization of Exhaust from a Modern Container Ship at Sea" Env. Sci. Tech. 2008

Measurement Methods and Instrumentation

PM Instruments

Instrument	Description
AVL MSS 483	AVL's micro soot sensor (photo acoustic abs. 808 nm)
DMM	Dekati's mass monitor (aerodynamic size separation)
EEPS	Engine Exhaust Particle Sizer Spectrometer
PAX	Photoacoustic Extinctiometer (photo acustic abs. 870 nm)
AE33	Aethalometer – filter paper transmission
MAPP	Multi-angle absorption photometer (absorption 670nm)
fSMPS	In-house fast scanning mobility particle sizer 7 to 200 nm
nSMSP	In-house nano scanning mobility particle sizer 3 to 60 nm
3776 CPC	TSI condensing particle sizer 2.5 nm cut
3022A CPC	TSI condensing particle sizer 7 nm cut
3771 CPC	TSI condensing particle sizer 11 nm cut
3025A CPC	TSI condensing particle sizer 3 nm cut
Sulfate IC	Sulfate ion chromatography
EC/OC	Sunset laboratories elemental organic PM analyzer





Ambient aerosol related instruments

Instrument	Description
TDL	Tunable diode laser spectroscopy ammonia measurement
HPLC	High performance liquid chromatograph carbonyls analysis
GC	Gas chromatographs for speciated hydrocarbon analysis
AMS	Aerodyne aerosol mass spectrometer chemical characterizations
APM	Kanomax aerosol particle mass analyzer for density
TDMA	Tandem differential mobility analyzer
LC-TOFMS	Liquid chromatograph time-of-flight mass spectrometer