Quantifying Aircraft Black Carbon Emissions

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Cambridge Particle Meeting
24th May 2013

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Outline

- Context
- Experimental study
  - Aerosol characterisation
  - Effect of particle size and measurement variability on correlation between mass concentration and SN
- Global aircraft BC emissions
- Conclusions

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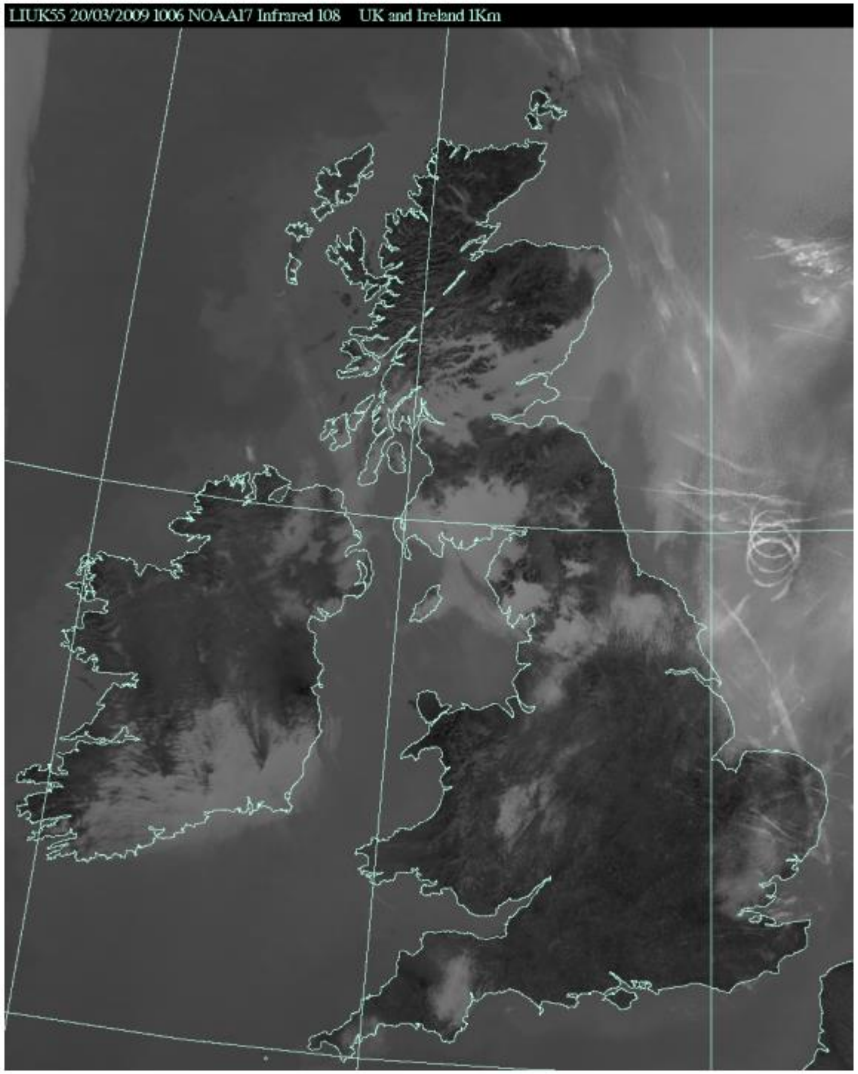
Motivation

- Aircraft gas turbine engines emit PM
  - Focus on non-volatile black carbon (BC) mass
- Climate impacts (direct and in-direct) and health impacts
- Limited measurement data
- Engine lifetimes of ~decades, new regulations (SAE E-31) unlikely to be applied to engines currently in service

Contrail cirrus



Haywood, J.M., et al. 2009. JGR 114, D24201.

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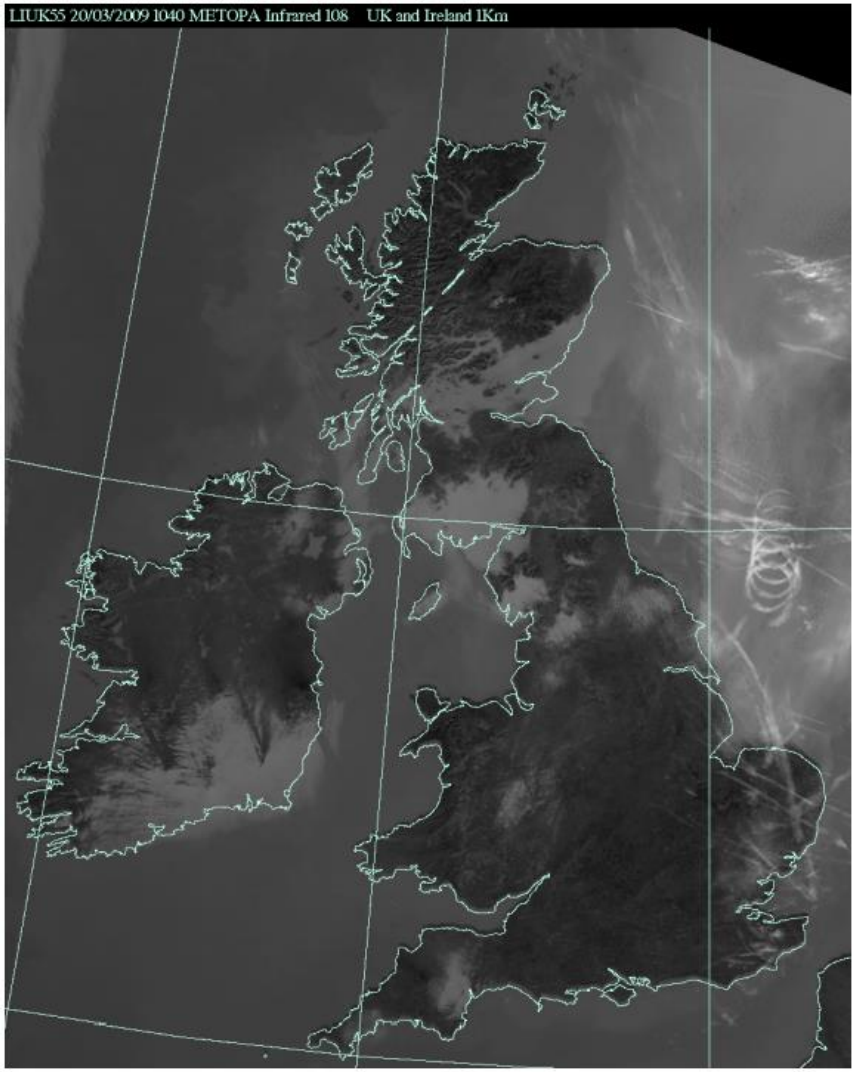

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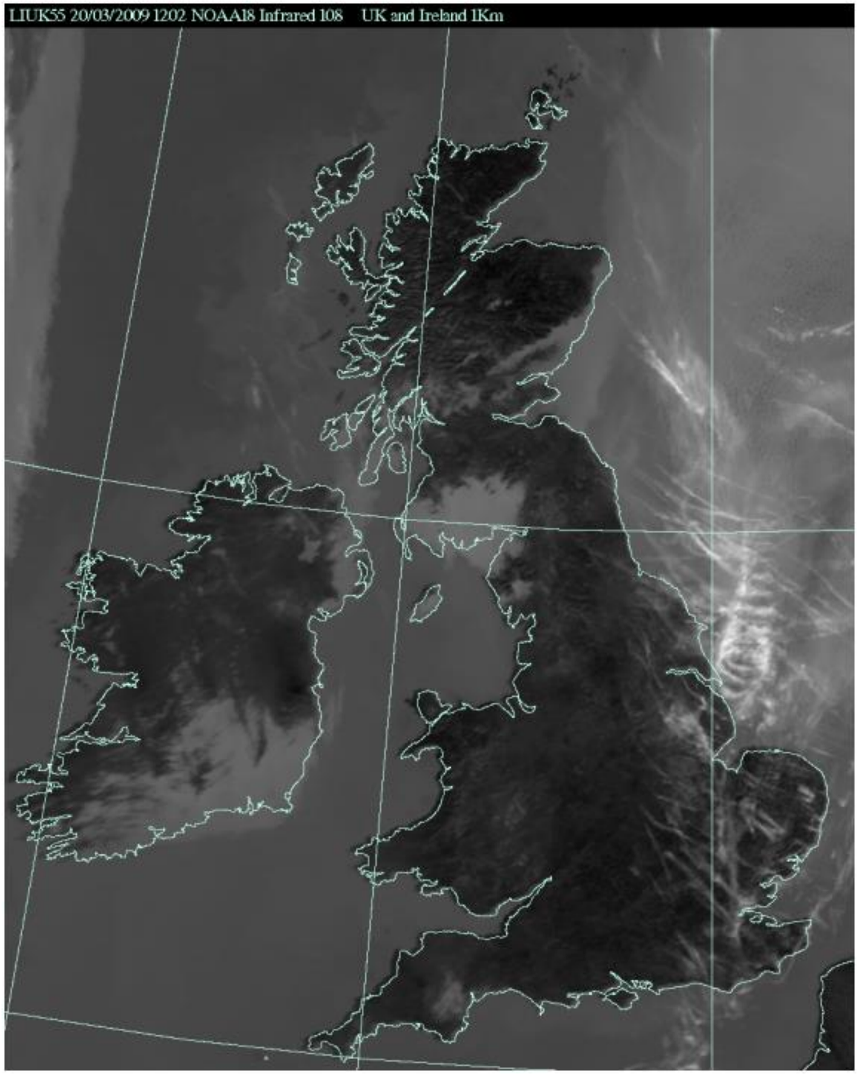

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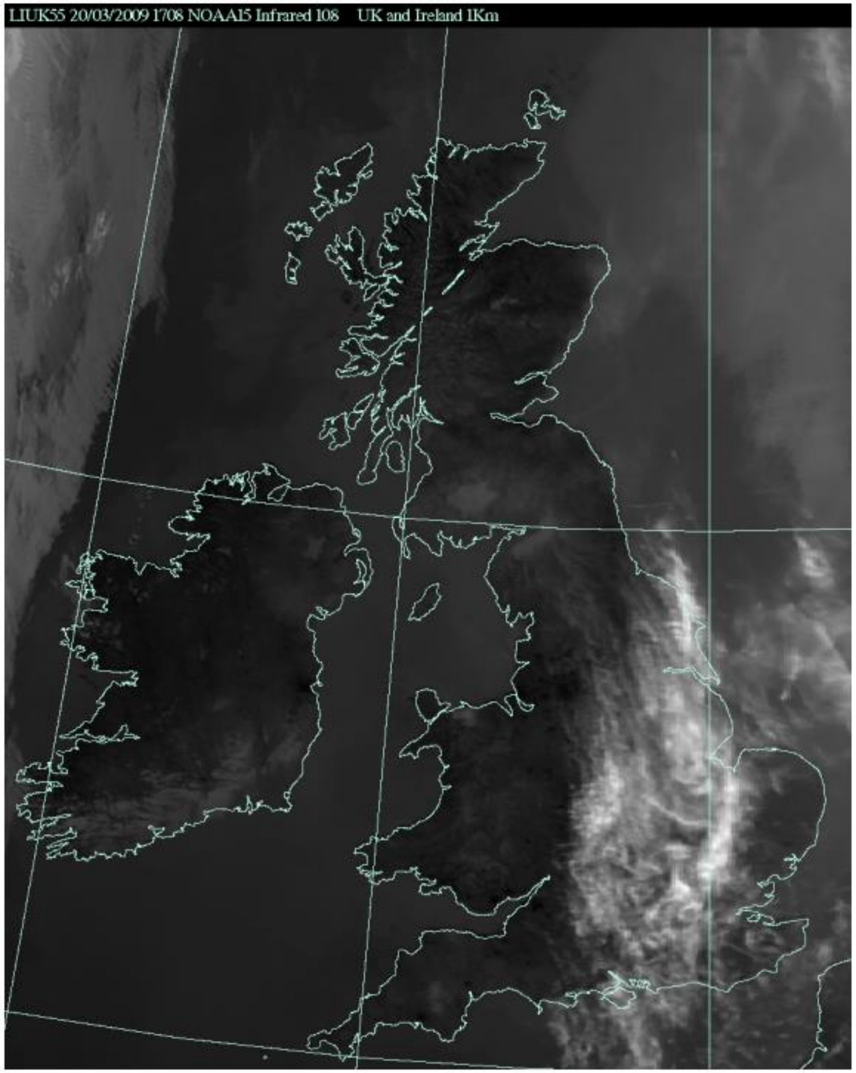

Haywood, J.M., et al. 2009. JGR 114, D24201.

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Aircraft Smoke Number

- Regulation introduced in 1981 to reduce plume visibility

Boeing 707, circa 1960

Aircraft Smoke Number

- No engines since 1990 have exceeded regulatory limit

Boeing 787, circa 2011

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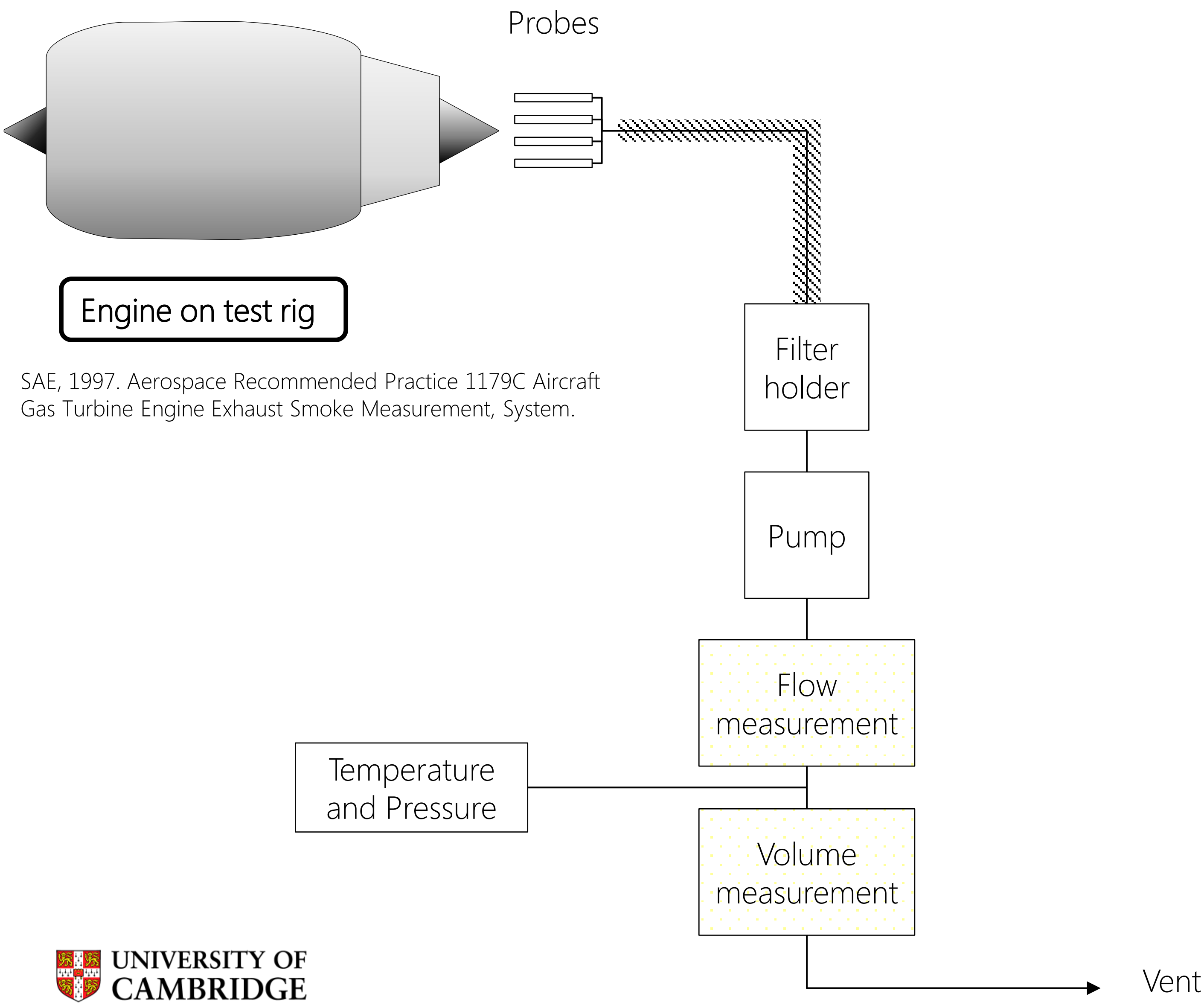
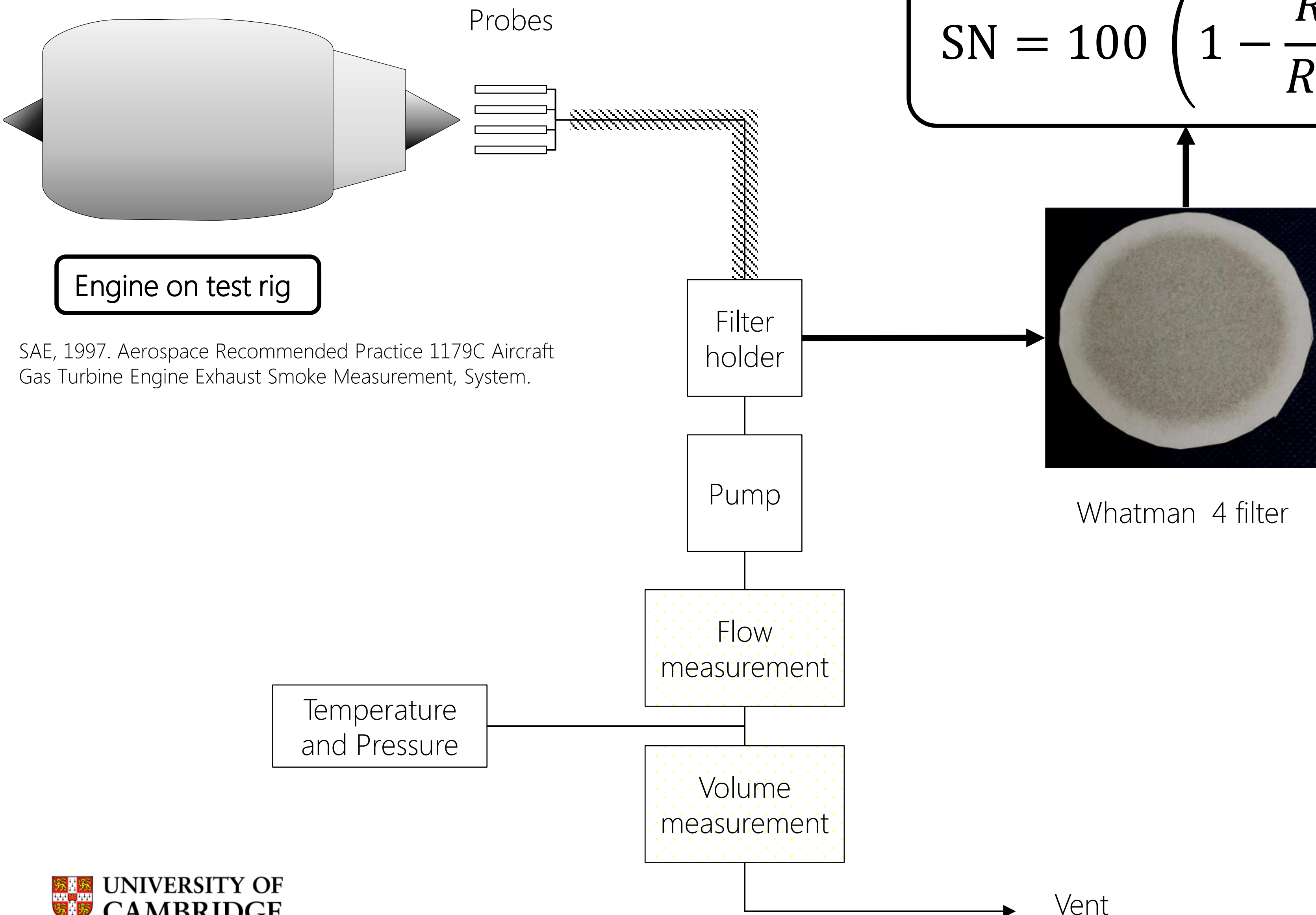
SN measurement



SAE, 1997. Aerospace Recommended Practice 1179C Aircraft Gas Turbine Engine Exhaust Smoke Measurement, System.

SN measurement

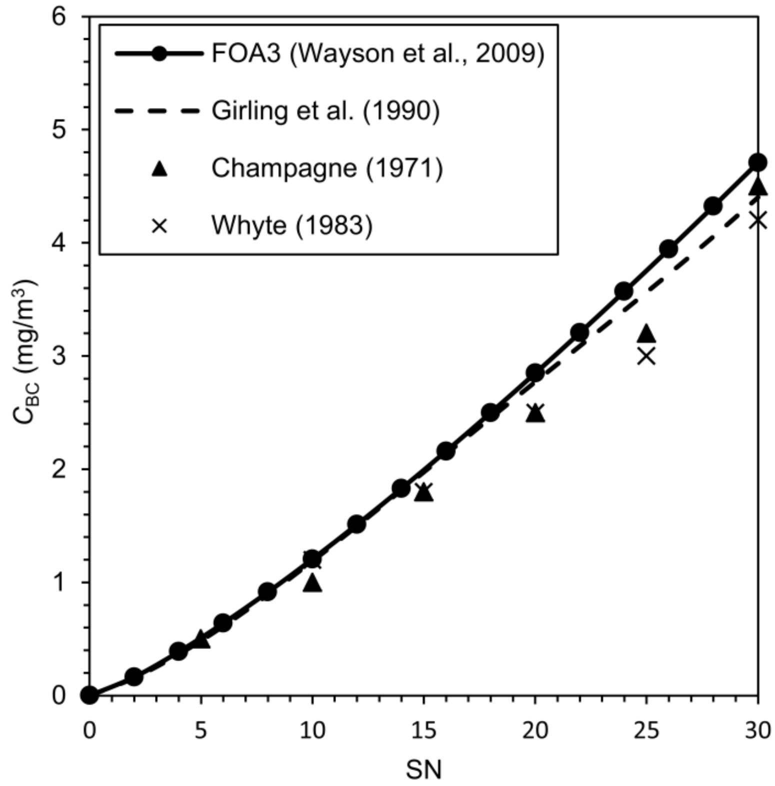


$$\mathrm{SN} = 100\left(1 - \frac{R_{\mathrm{end}}}{R_{\mathrm{start}}}\right)$$

SAE, 1997. Aerospace Recommended Practice 1179C Aircraft Gas Turbine Engine Exhaust Smoke Measurement, System.

SN to BC mass concentration

- Several studies have correlated SN to BC mass concentration (C_{BC})



Champagne, D.L., 1971. ASME paper 71-GT-88.
Girling, S.P., Hurley, C.D., Mitchell, J.P., Nichols, A.L., 1990. Aerosol Science and Technology 13, 8–19.
Wayson, R., Fleming, G., Iovinelli, R., 2009. Journal of the Air & Waste Management Association 59, 91–100.
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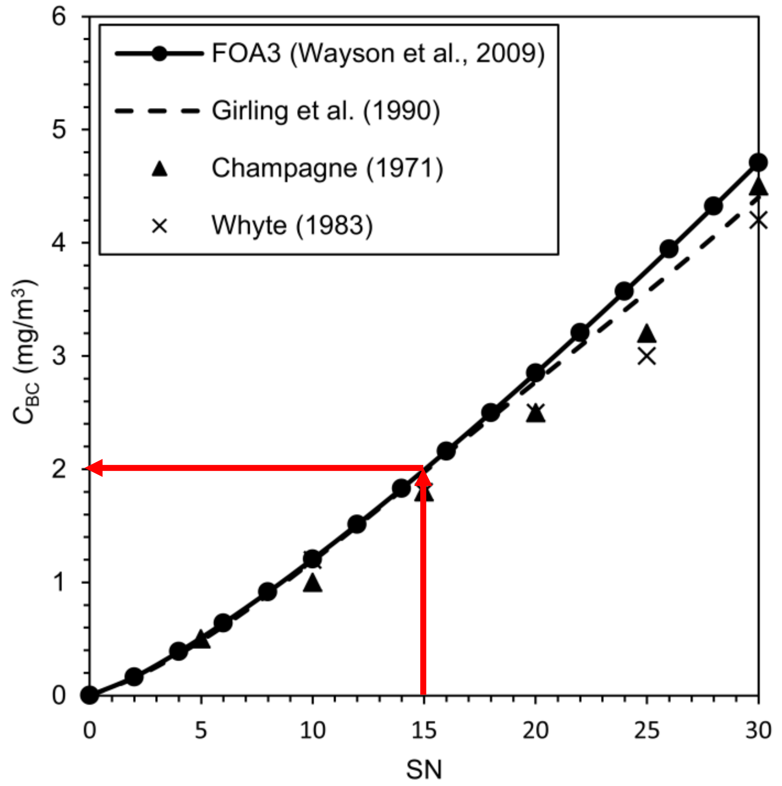

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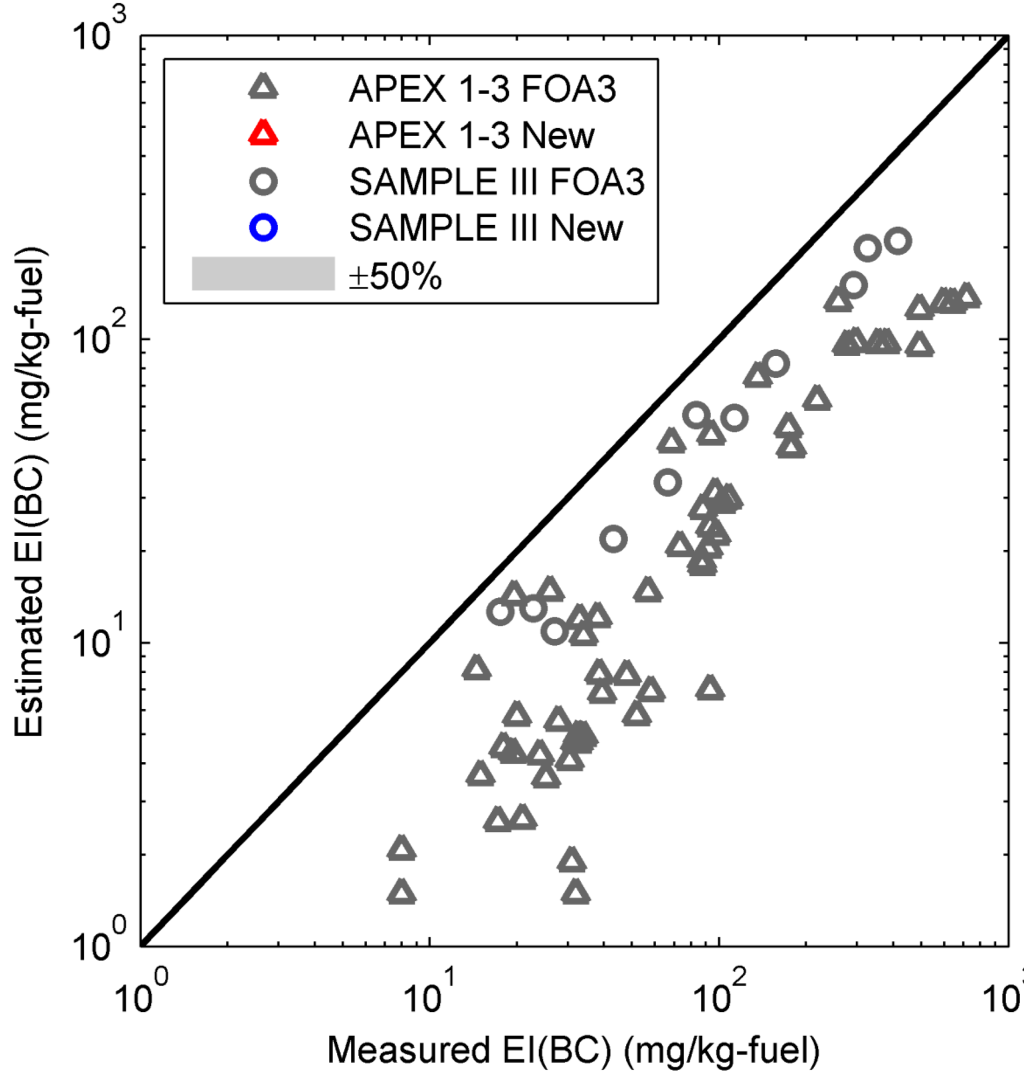
SN to estimate aircraft BC emissions

- First Order Approximation v3 method (FOA3)
- Developed in International Civil Aviation Organization CAEP meetings
- Estimate BC emissions during landing and take-off

ICAO, 2011. Airport Air Quality Guidance Manual.
Wayson, R. et al. (2009). *J Air & Waste Management Association*, *59*(1), 91–100.

Validation of existing SN-C_{BC} correlation

- Measurement data of SN and EI(BC)
  - APEX 1-3
  - SAMPLE III
- FOA3:
  - Consistent underestimation
  - APEX 1-3 underestimated by ×5 on average
  - Scatter in data
- Correlation between SN and C_{BC}?
  i. Effect of particle size distribution
  ii. SN measurement variability



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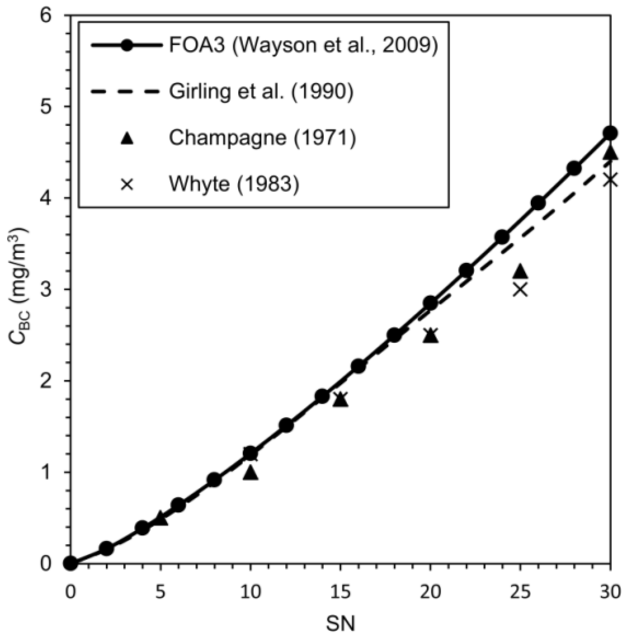
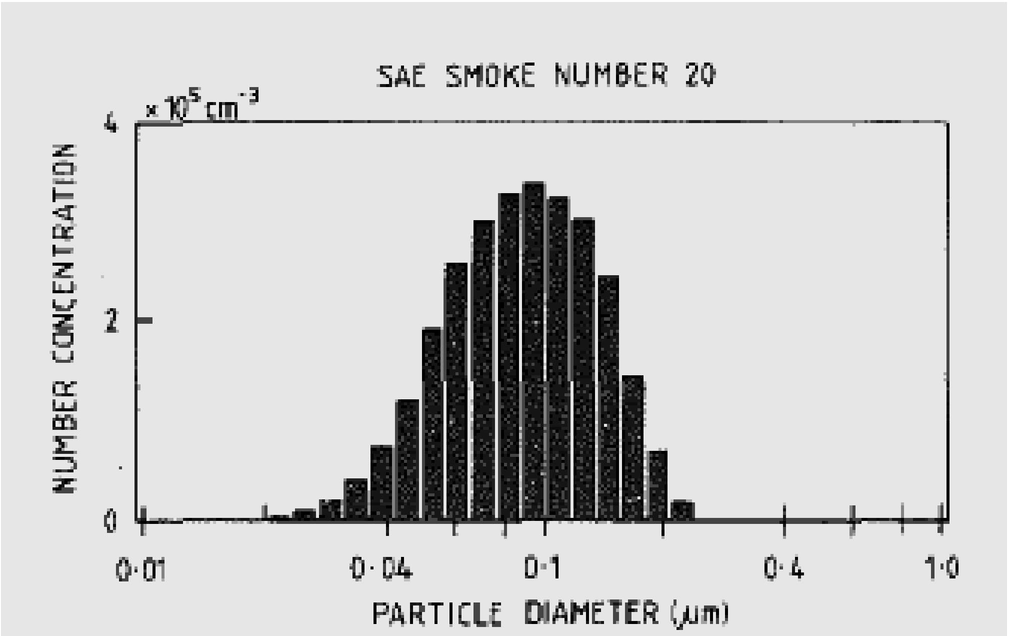
(i) Particle size distribution

- Empirical correlation between SN-C_{BC} derived for soot with GMD = 80-100 nm (Girling et al., 1990)
- **Inconsistent with aircraft measurements (GMD = 20-40 nm)**





Source: Girling, S. P., et al. (1990).

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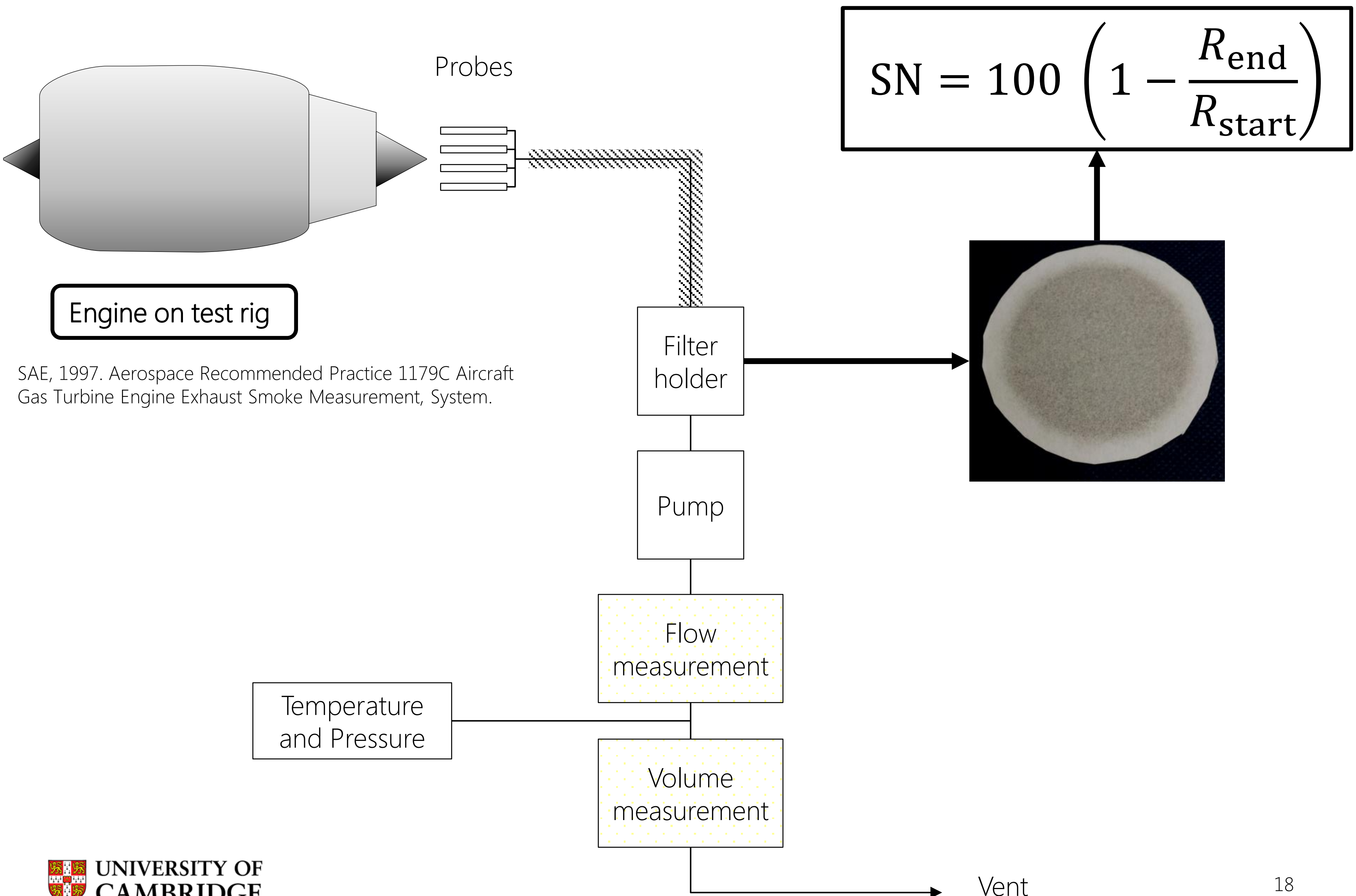
(ii) SN measurement variability

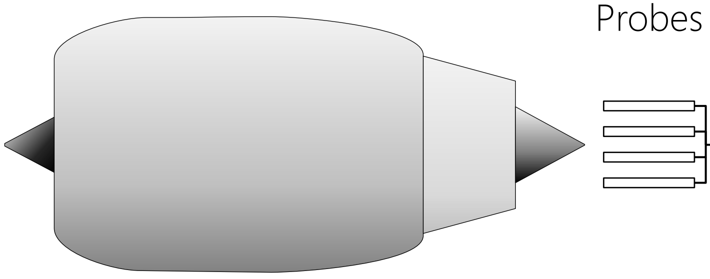


$$SN = 100\left(1 - \frac{R_{\mathrm{end}}}{R_{\mathrm{start}}}\right)$$

SAE, 1997. Aerospace Recommended Practice 1179C Aircraft Gas Turbine Engine Exhaust Smoke Measurement, System.

(ii) Filter diameter variability

Probes



Engine on test rig

SAE, 1997. Aerospace Recommended Practice 1179C Aircraft Gas Turbine Engine Exhaust Smoke Measurement, System.

Filter holder

Pump

Flow measurement

Temperature and Pressure

Volume measurement

Vent

Sample line temperature: 60 – 175°C

Sample line length: up to 25 m

Sample line diameter: 4 – 8 mm

Filter diameter: 19.0 – 37.5 mm

Face velocity: 20 – 80 cm/s

Flow rate: 14 L/min

Mass: 16.2 kg of exhaust per m^2

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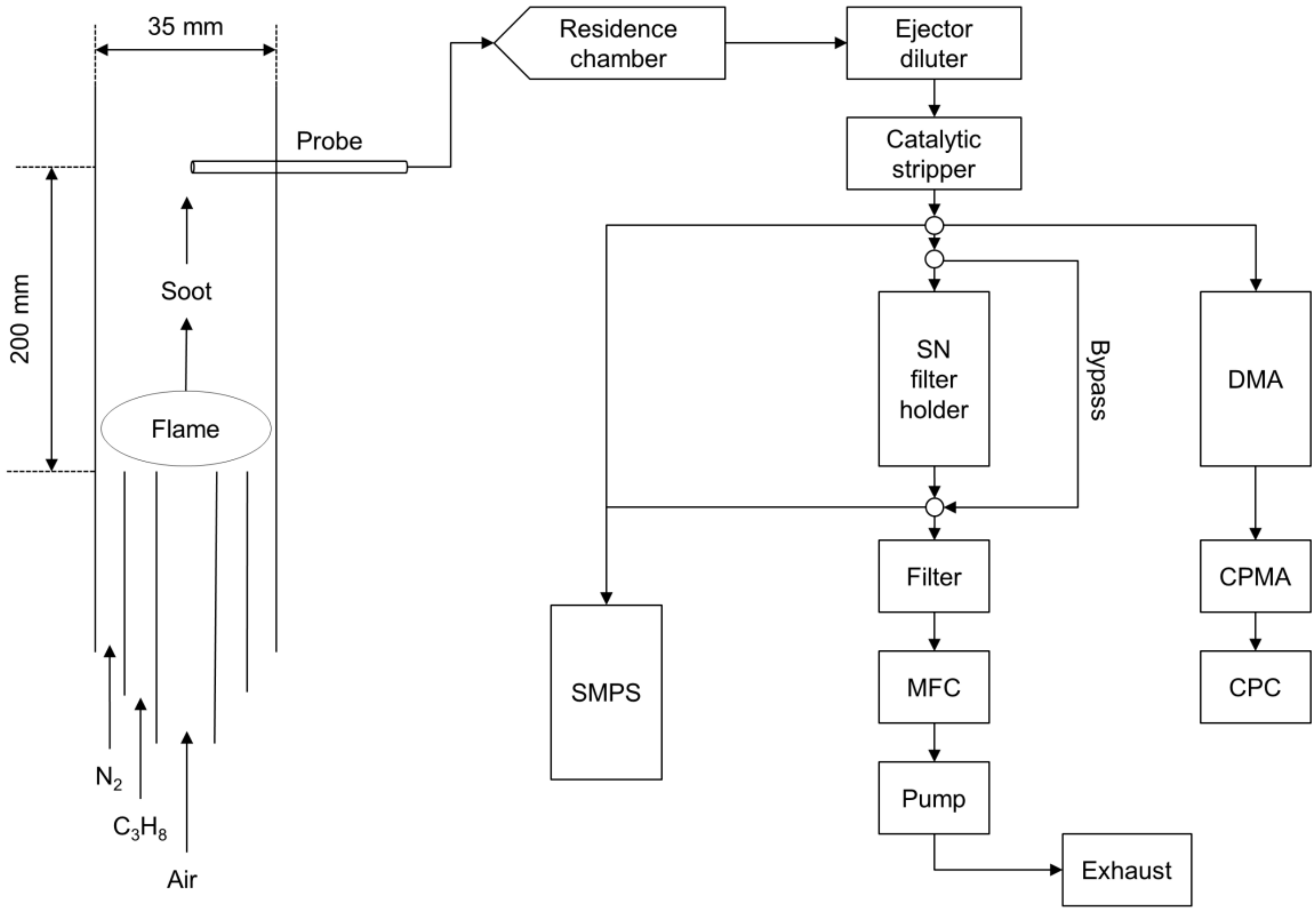
Experimental set-up



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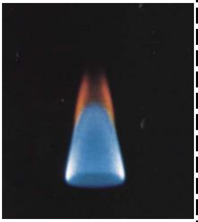

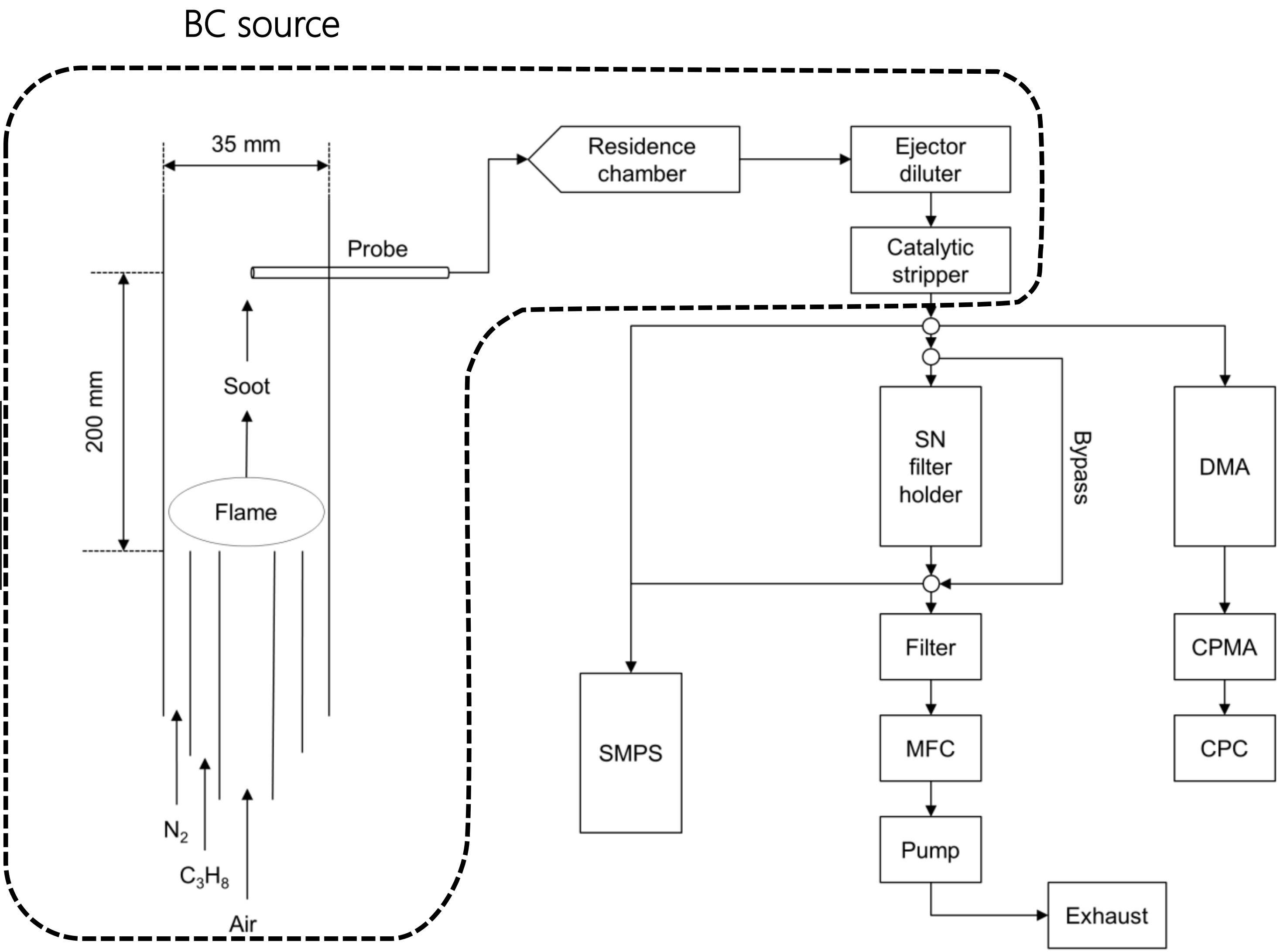

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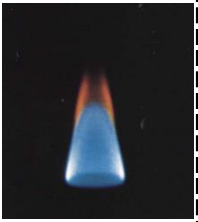

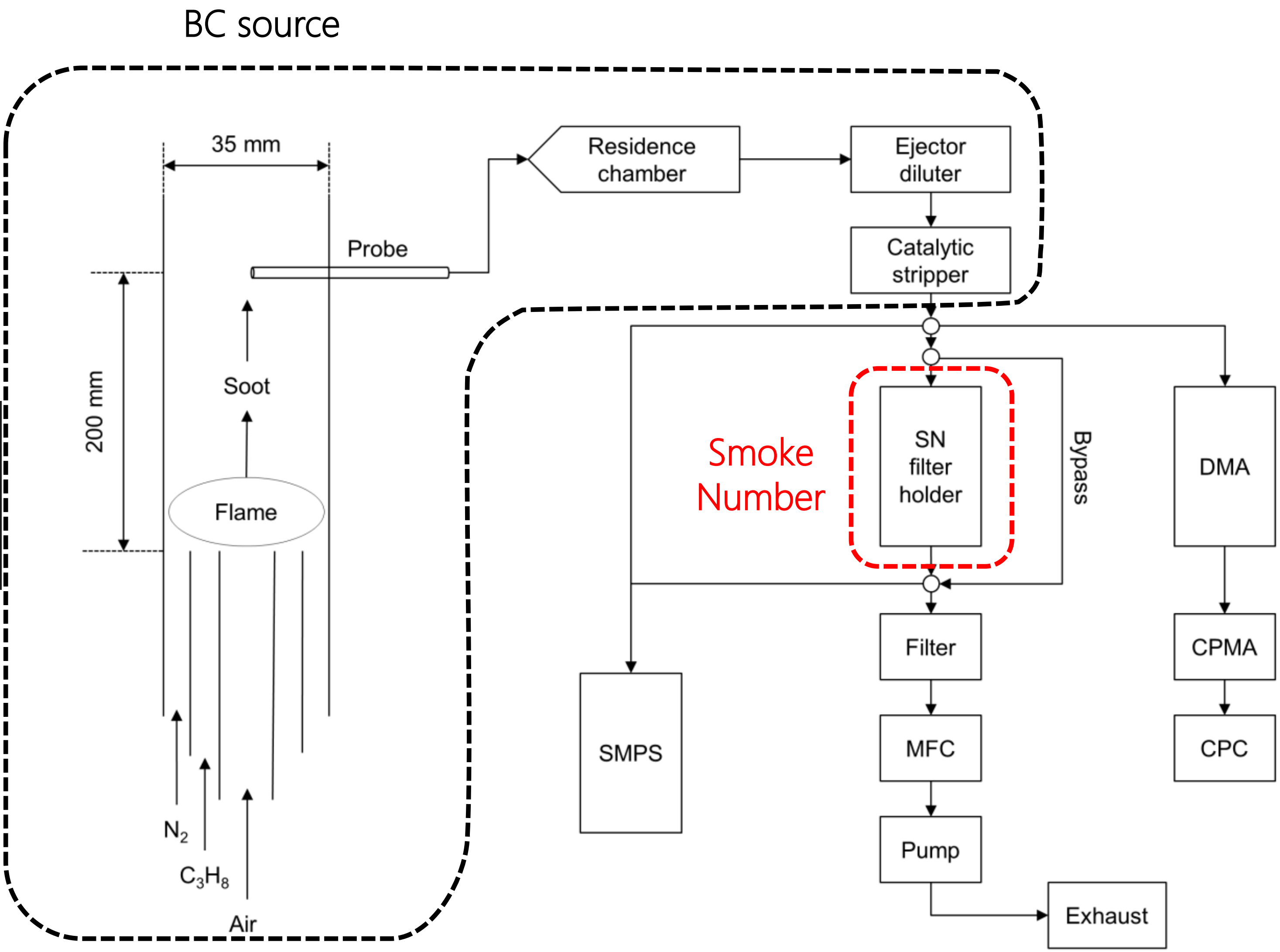

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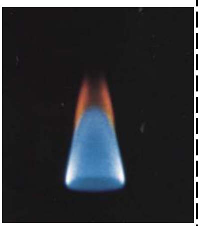

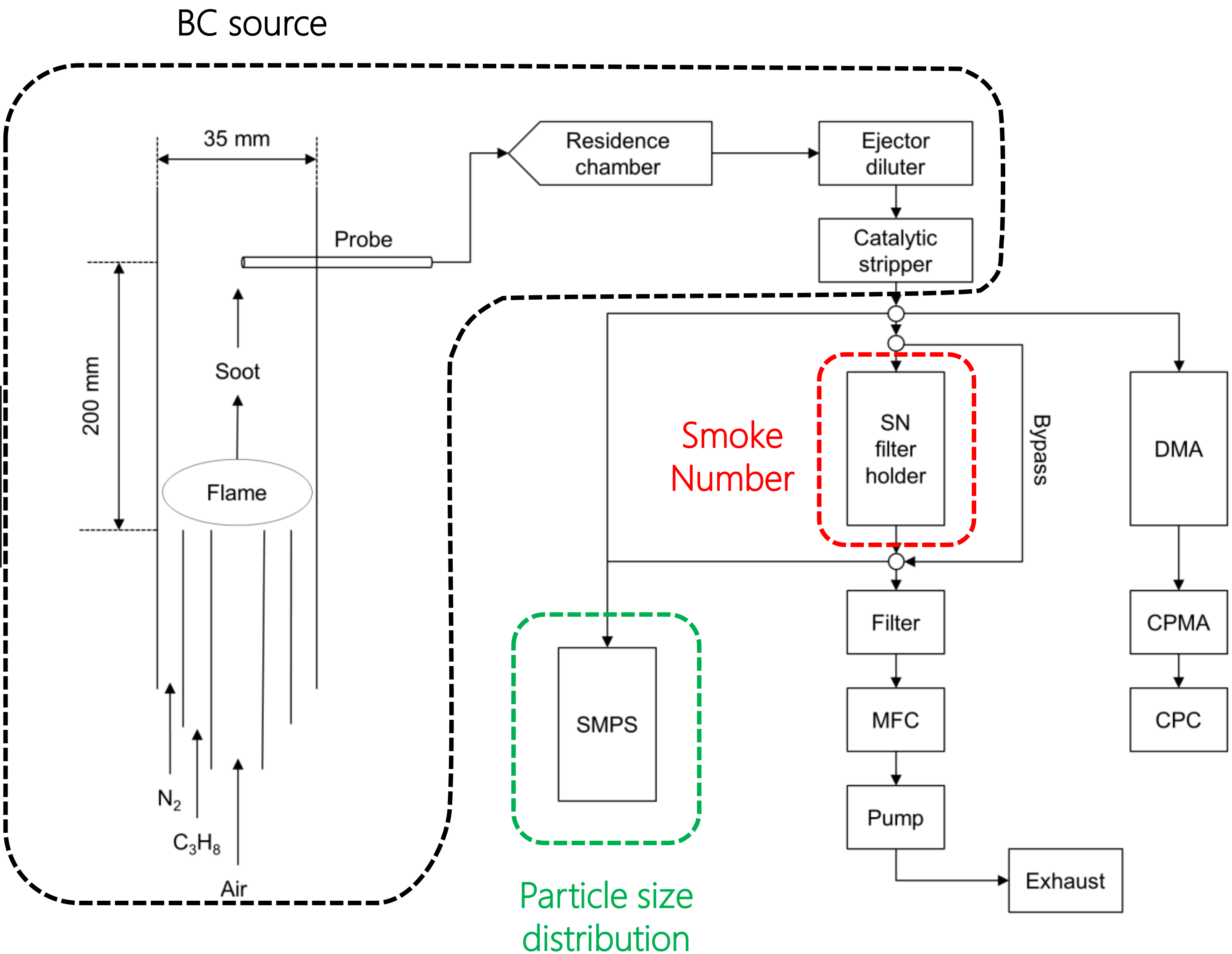

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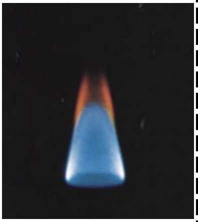

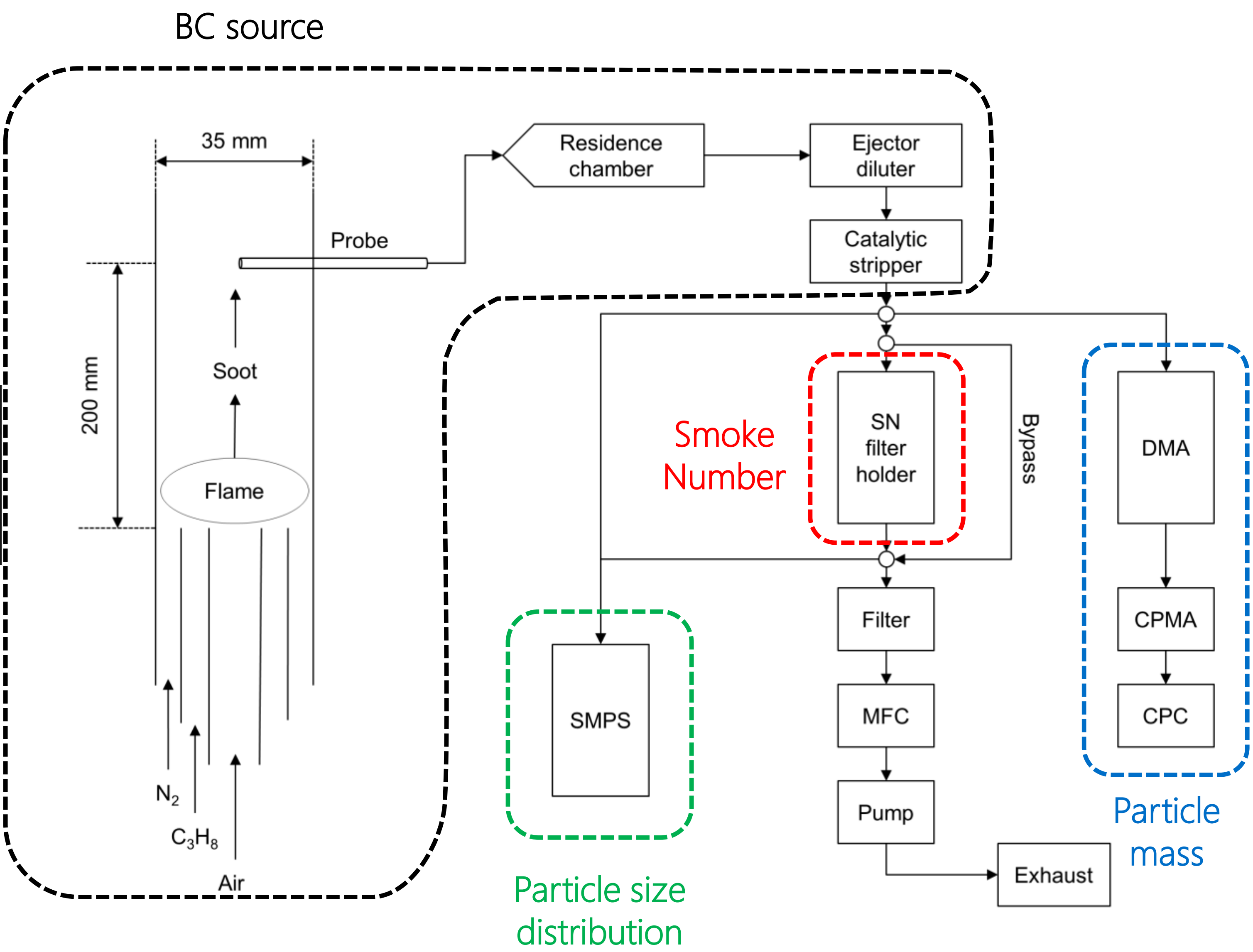

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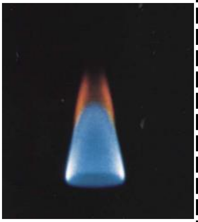

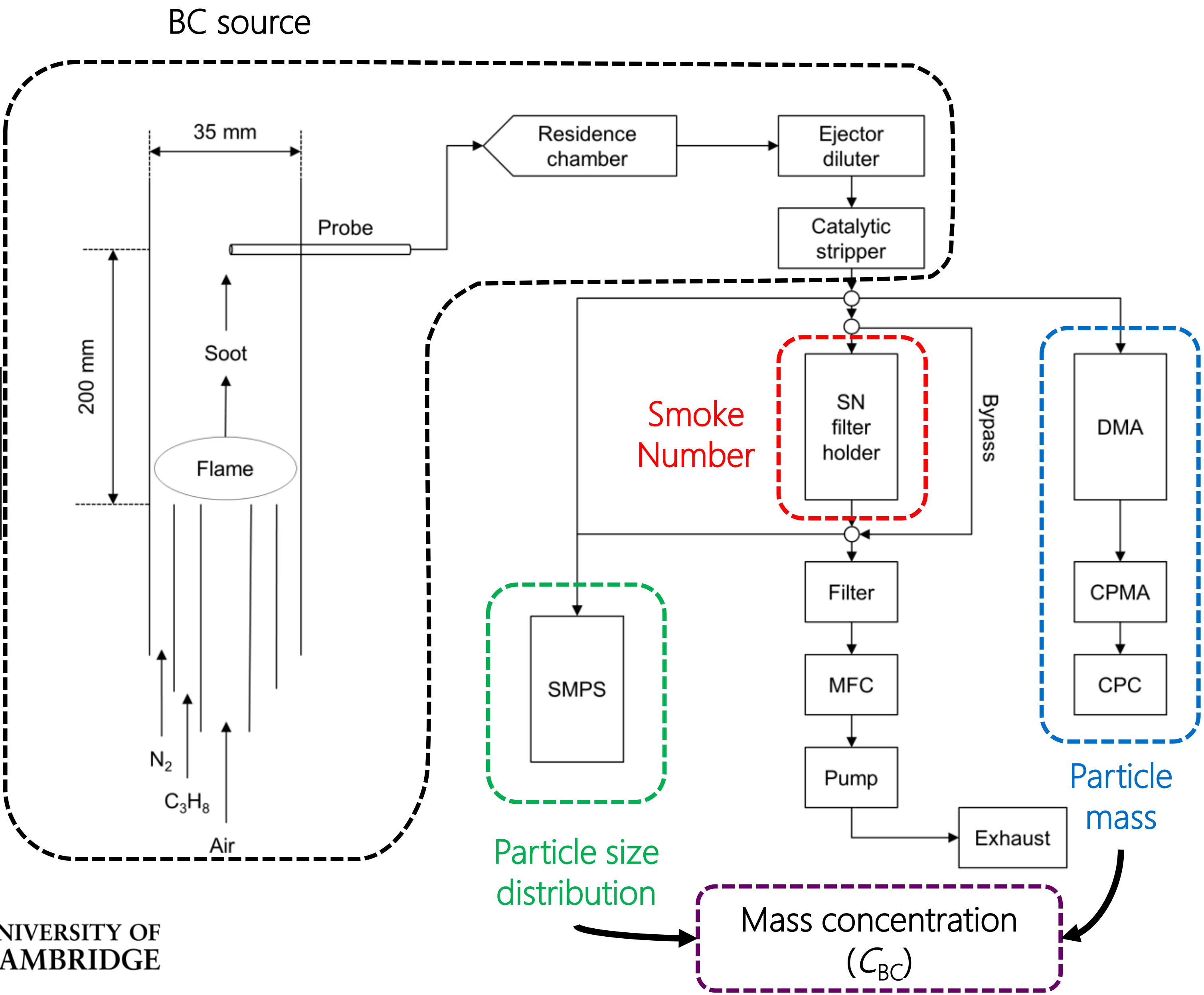

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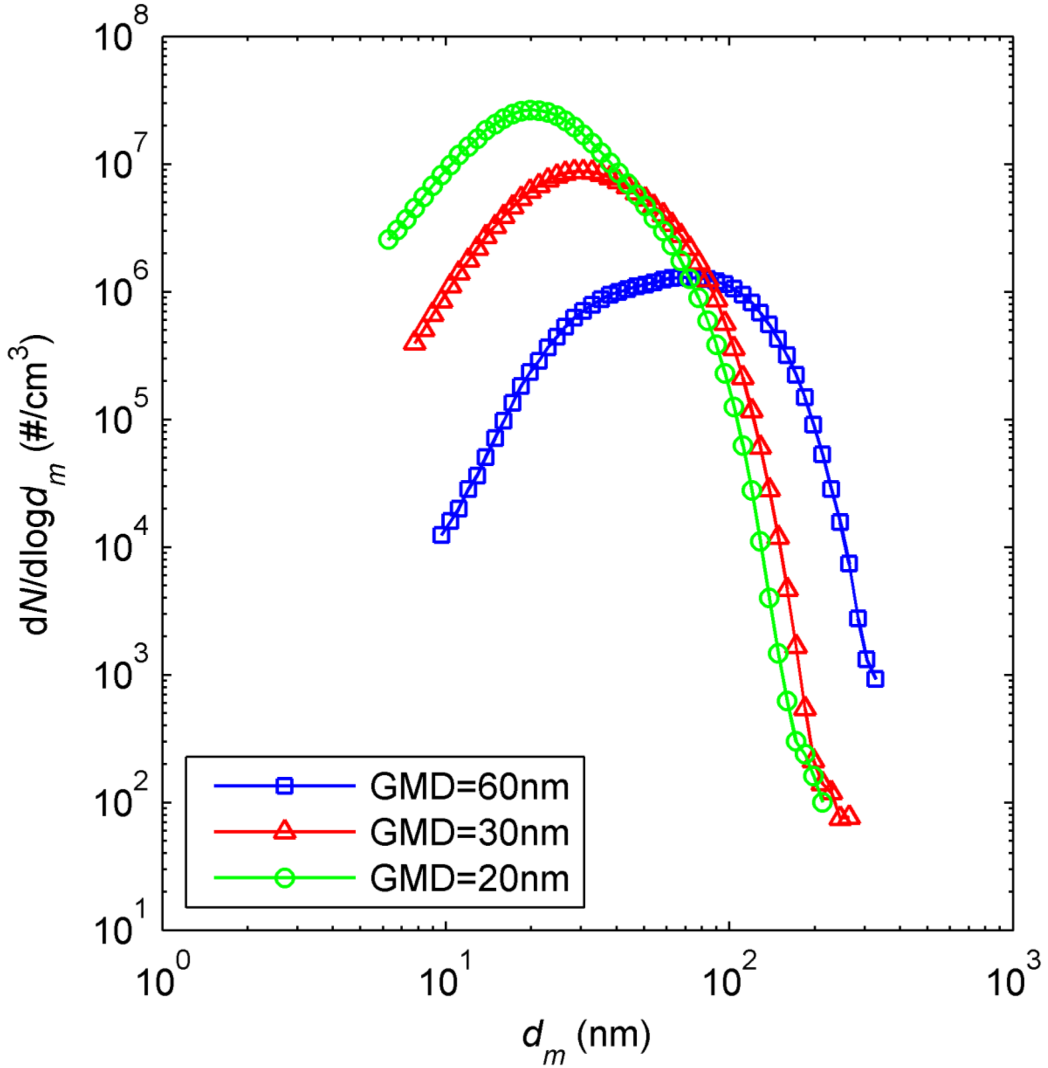
Particle size distributions



	GMD (nm)	GSD
(blue)	60.4	1.79
(red)	30.5	1.65
(green)	20.0	1.62

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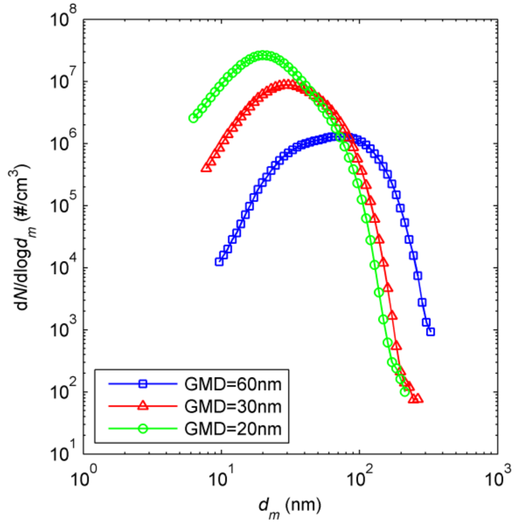
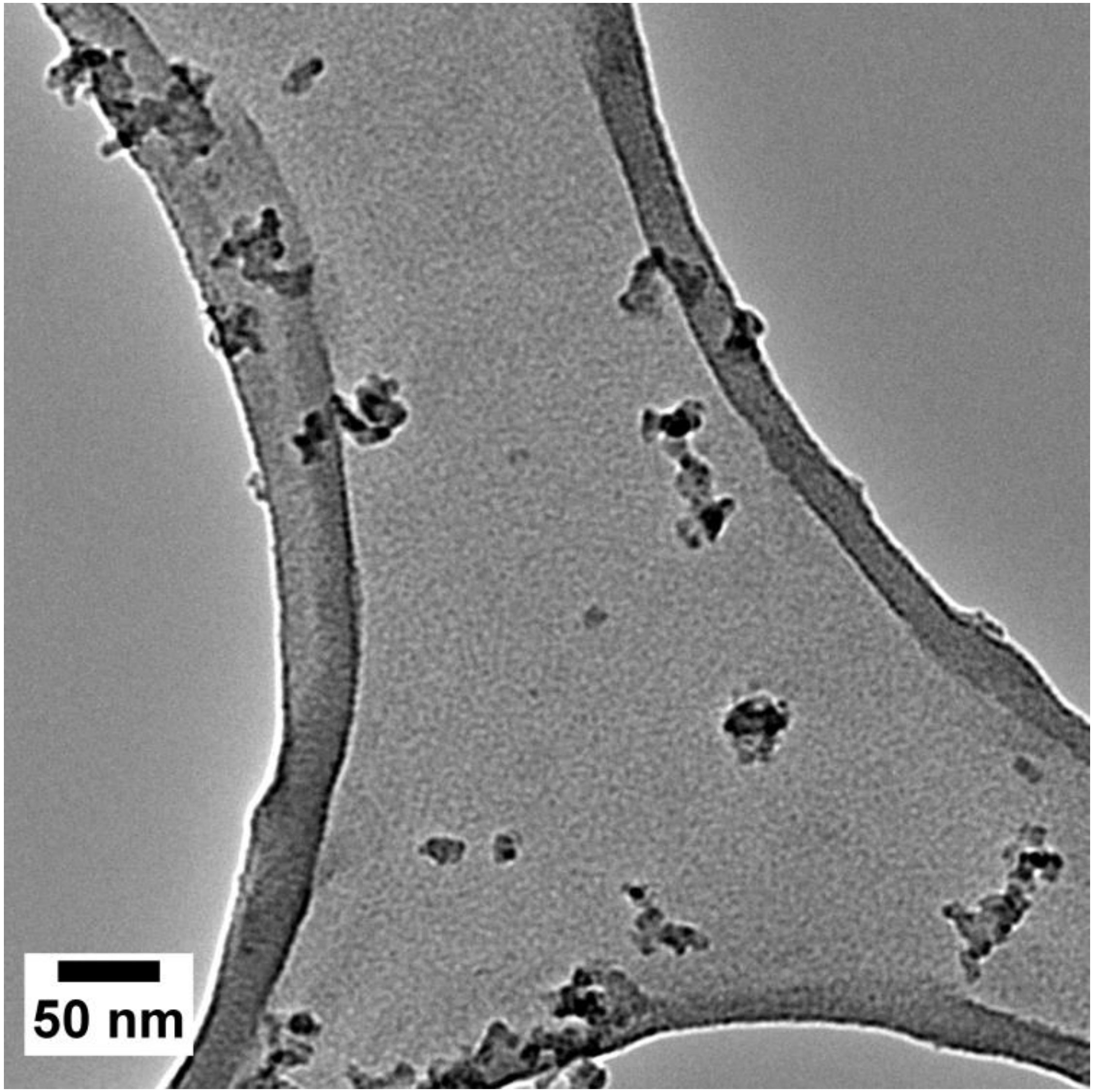
Morphology



- BC aggregates:
  - Open structure
  - Spherical
- Primary particle size <20 nm



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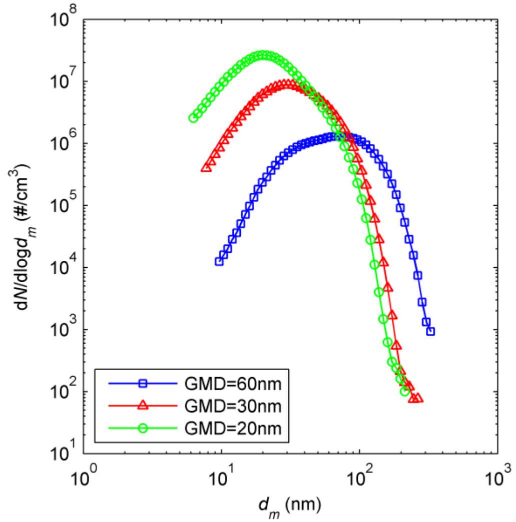
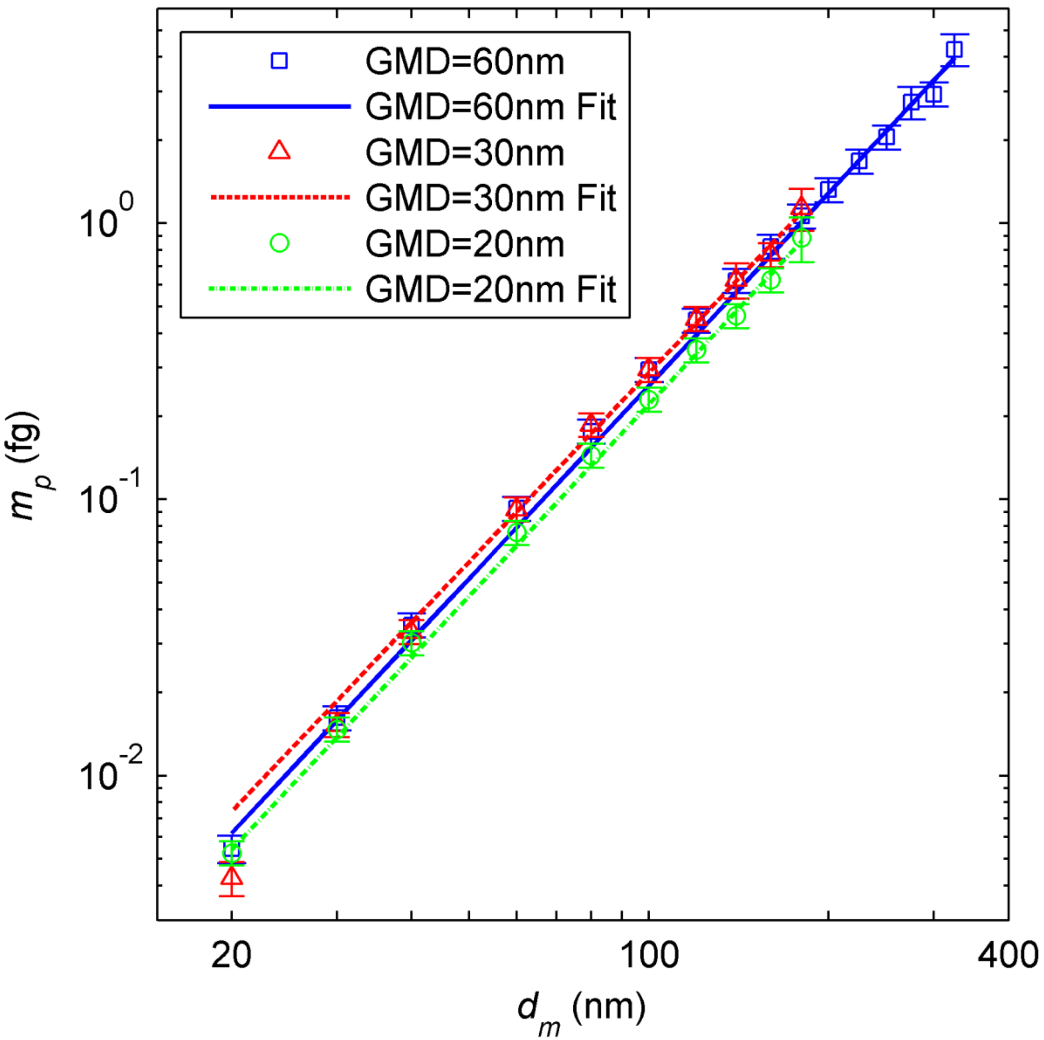
Morphology



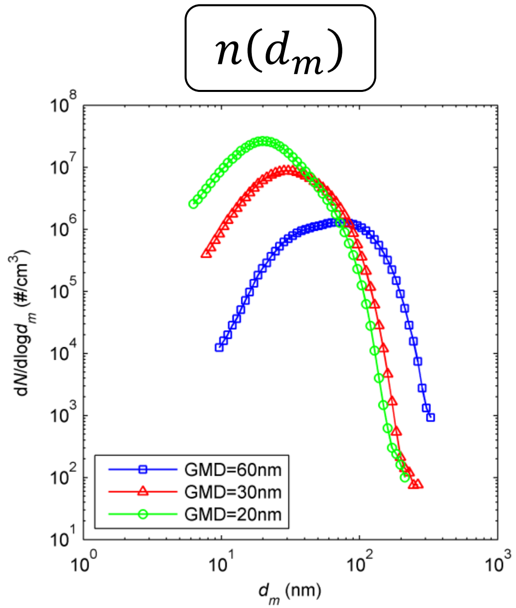
$$m_p\,[\mathrm{fg}] = C_m\, d_m^{D_m}$$

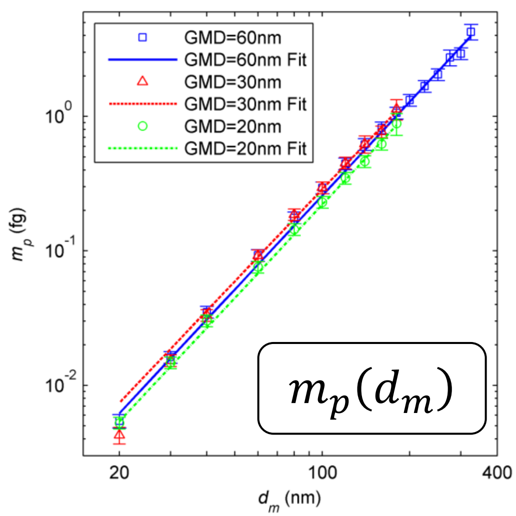
- Particle mass as a function of mobility diameter
- D_m is the mass-mobility exponent (D_m=3 for spheres)
- D_m ~ 2.3



Sorensen, C.M., 2011. Aerosol Science and Technology 45, 765–779.

BC mass concentration





$$C_{\mathrm{BC},\rho_{\mathrm{eff}}} = \int_0^{\infty} n(d_m) m_p(d_m)\, \mathrm{d}d_m$$

- Estimate mass concentration
  - particle number distribution: $n(d_m)$
  - particle mass: $m_p(d_m)$
- **±10% error** when compared to gravimetric analysis

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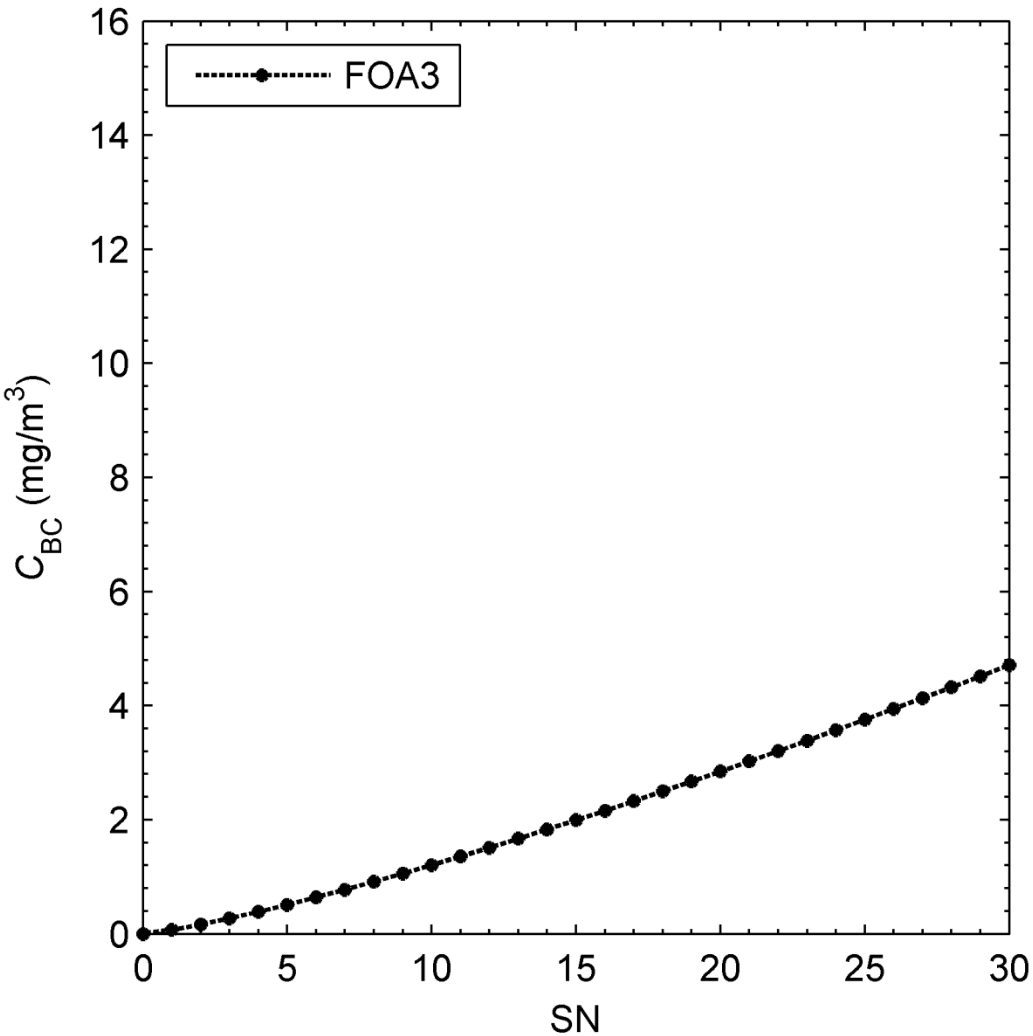
SN-C_{BC}

- Correlation between SN and C_{BC}
- Impacts of:
  - Filter diameter
    - 19 mm (open)
    - 35 mm (filled)
  - Particle size distribution



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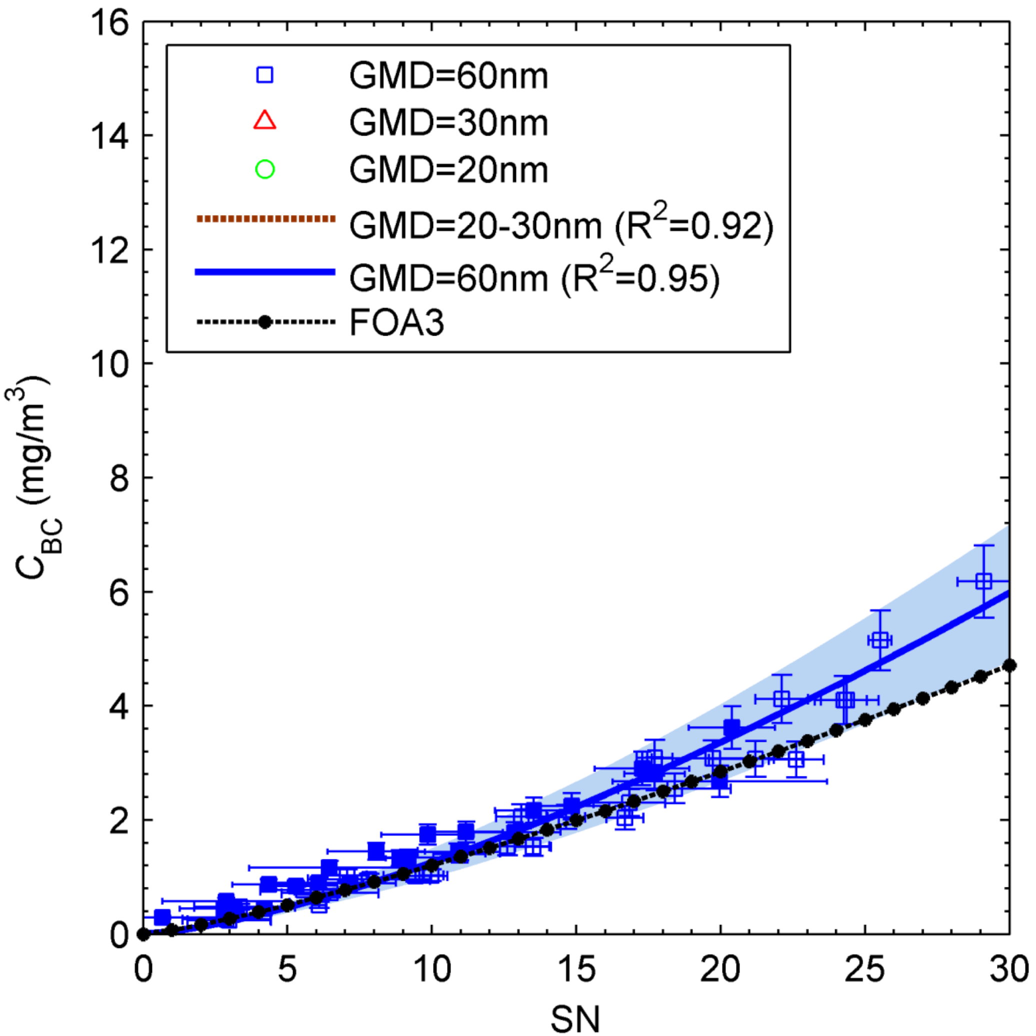
SN-C_{BC}

- Correlation between SN and C_{BC}
- Impacts of:
  - Filter diameter
    - 19 mm (open)
    - 35 mm (filled)
  - Particle size distribution
- GMD = 60 nm
  - Matches FOA3 correlation
  - FD not significant



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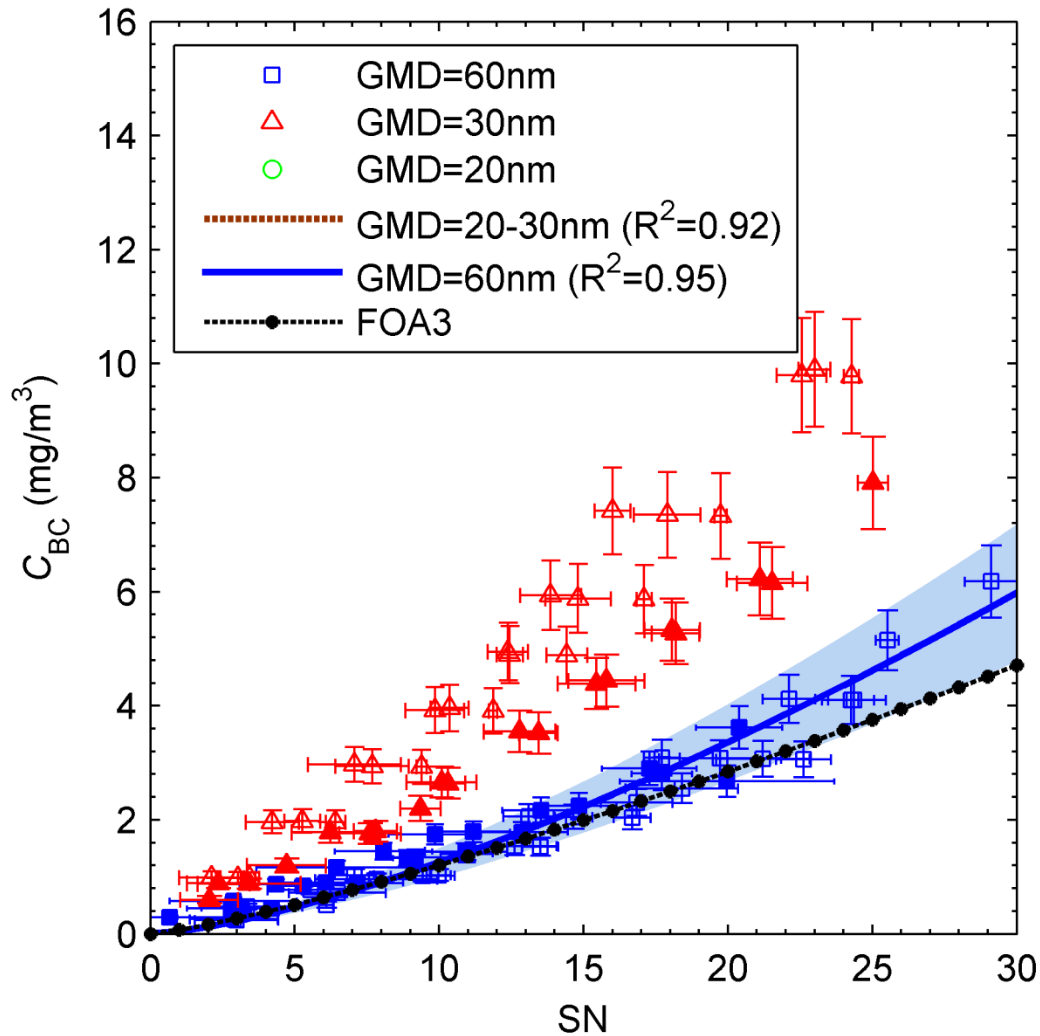
- GMD = 30 nm
  - Greater C_{BC} for a given SN
  - Less mass collected for 19 mm FD



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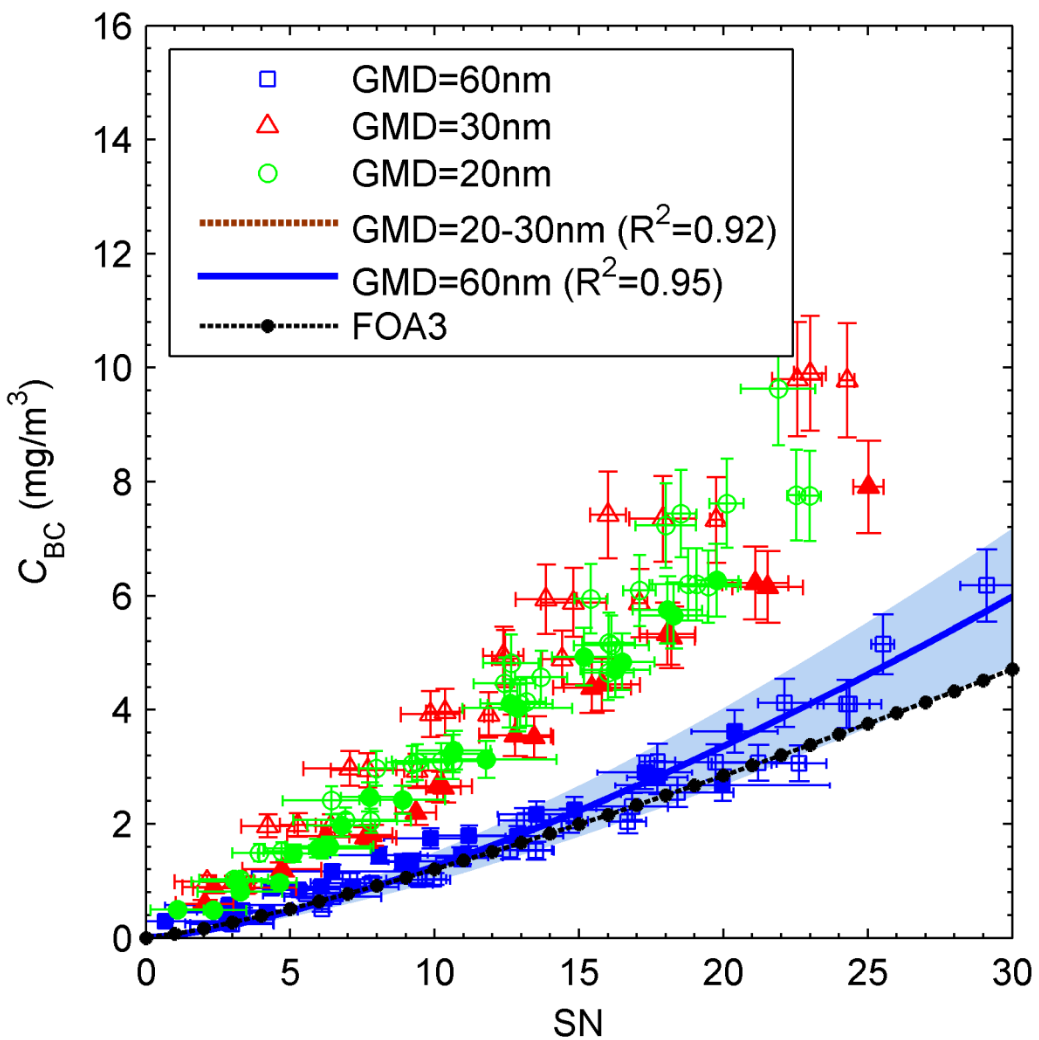
SN-C_{BC}

- Correlation between SN and C_{BC}
- Impacts of:
  - Filter diameter
    - 19 mm (open)
    - 35 mm (filled)
  - Particle size distribution
- GMD = 60 nm
  - Matches FOA3 correlation
  - FD not significant
- **GMD = 30 nm**
  - Greater C_{BC} for a given SN
  - Less mass collected for 19 mm FD
- **GMD = 20 nm**
  - Similar to 30 nm
  - FD not significant



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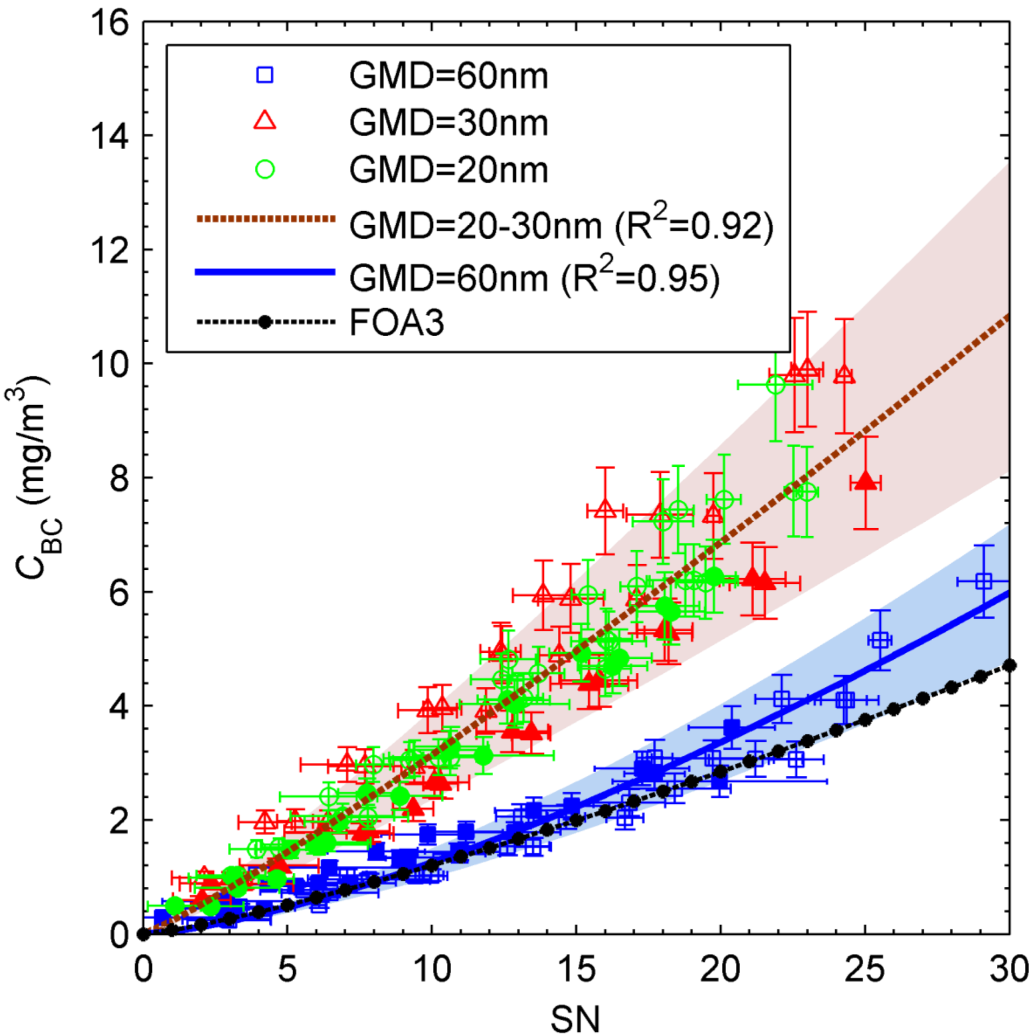
SN-C_{BC}

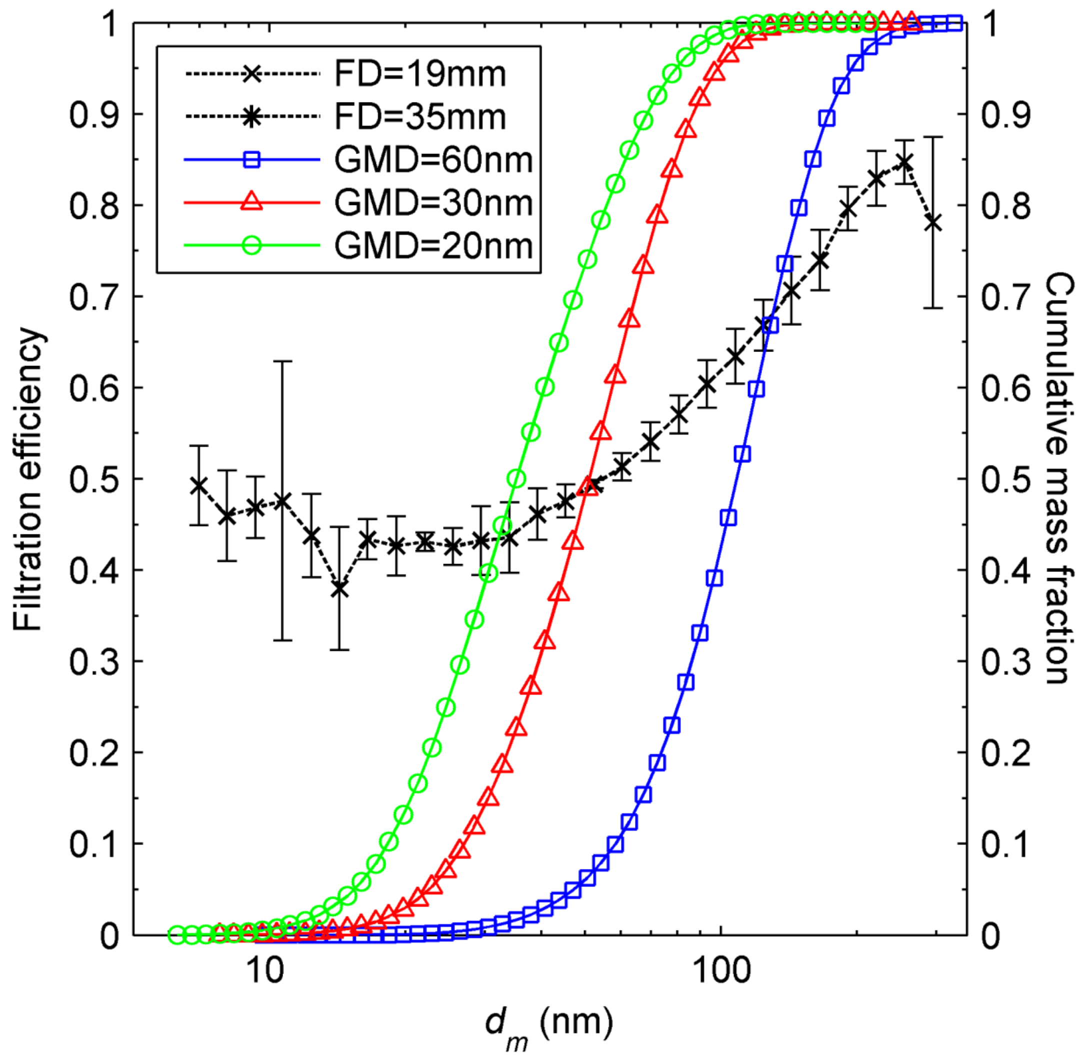
- Combine data for 20 and 30 nm GMD to represent aircraft BC

$$C_{BC}\left[\frac{\mathrm{mg}}{\mathrm{m}^3}\right] = 0.236(\mathrm{SN})^{1.126}$$

- ±25% uncertainty bound captures >95% of the data
- Predicted C_{BC} factor 3 greater and FOA3
- Suggests that the current correlation underestimates aircraft BC emissions

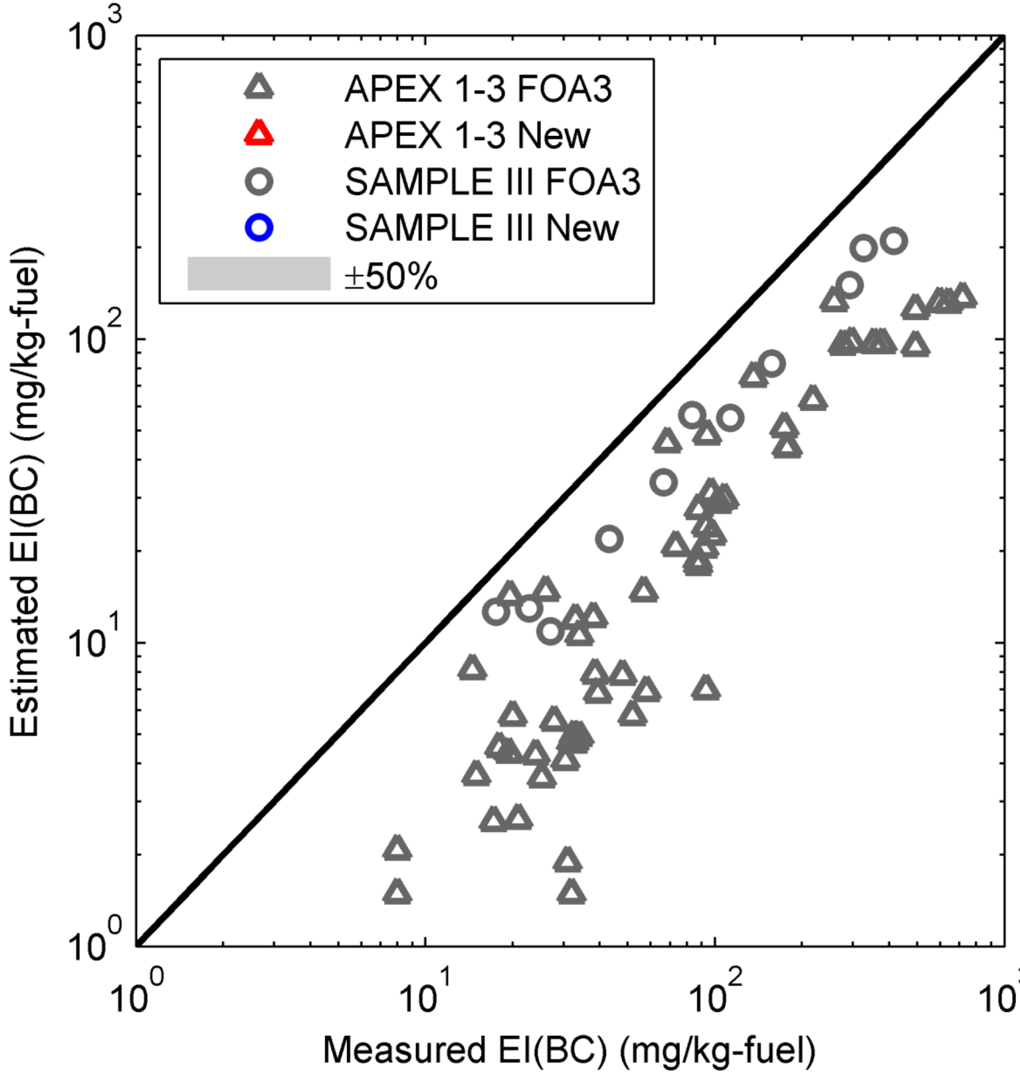


Filtration efficiency



Validation of new SN-C_{BC} correlation

- Measurement of SN and EI(BC)
  - APEX 1-3
  - SAMPLE III
- FOA3:
  - Consistent underestimation
  - APEX 1-3 underestimated by ×5 on average



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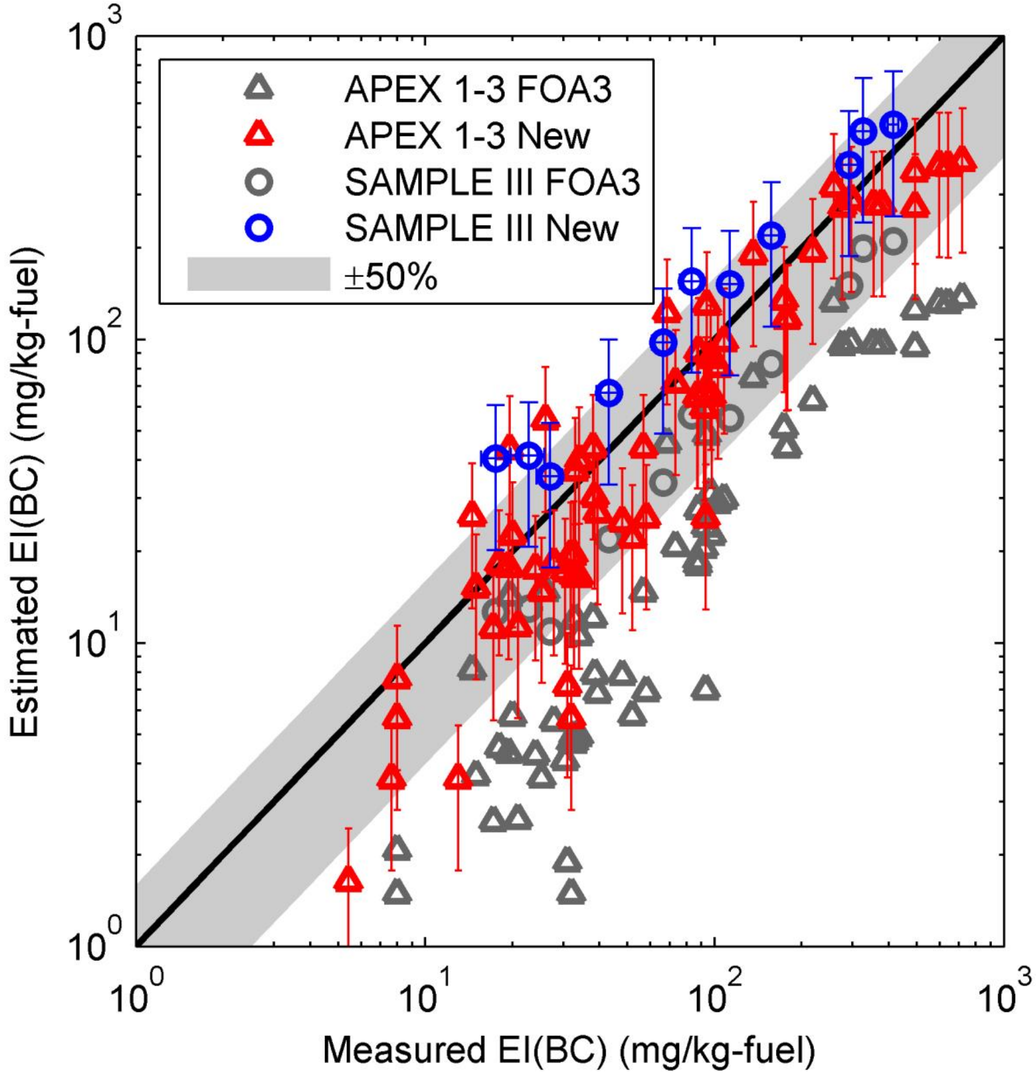
- Measurements of SN and EI(BC)
  - APEX 1-3
  - SAMPLE III
- FOA3:
  - Consistent underestimation
  - APEX 1-3 underestimated by ×5 on average
- New SN-C_{BC}
  - Improved estimates
  - APEX 1-3
    R^2=0.10 → 0.79
  - SAMPLE III
    R^2=0.56 → 0.74



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Validate estimated EI(BC)

- Measurements of aircraft EI(BC) from:
  - APEX 1-3 (Timko et al, 2010)
  - Delta-ATL (Lobo et al., 2008)
  - Agrawal et al. (2008)
  - SAMPLE III (Crayford et al., 2012)

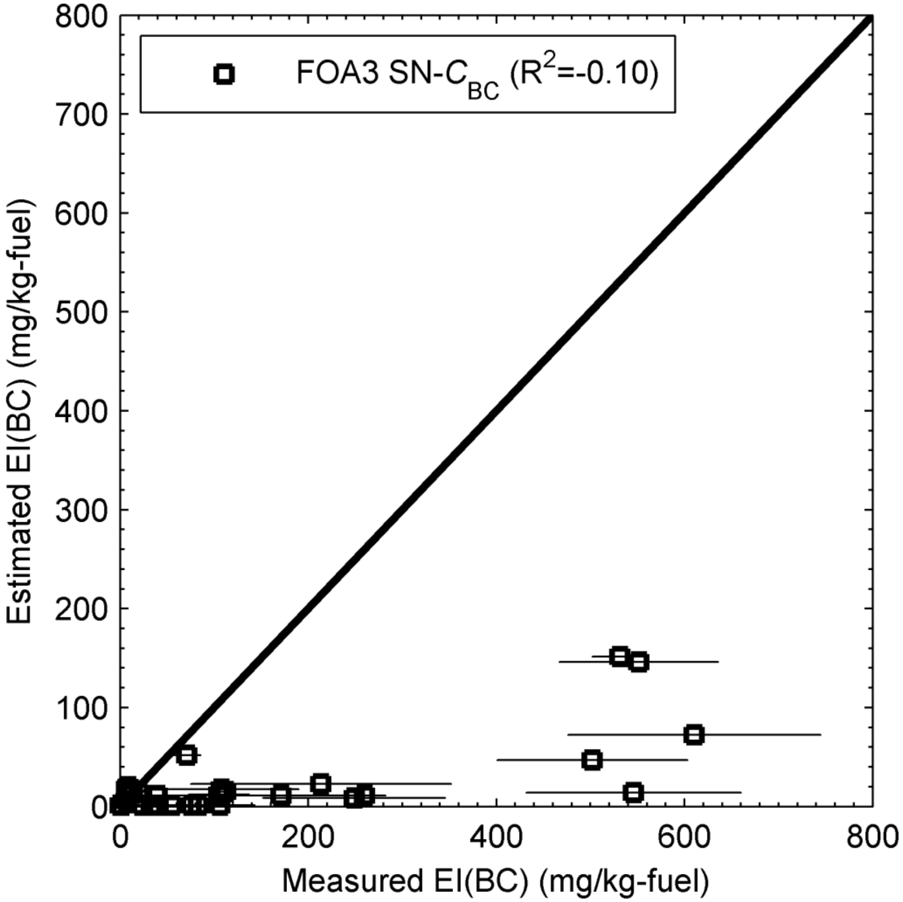
- Data for 13 engine models

- <u>Use certification SN to estimate EI(BC)</u>

Agrawal, H. et al., 2008. Atmospheric Environment 42, 4380–4392.
Crayford, A. et al., 2012. Studying, sAmpling and Measuring of aircraft Particulate Emissions III - SAMPLE III.
Lobo, P. et al., 2008. Delta - Atlanta Hartsfield (UNA-UNA) Study.
Timko, M.T. et al., 2010. Journal of Engineering for Gas Turbines and Power 132, 061505.

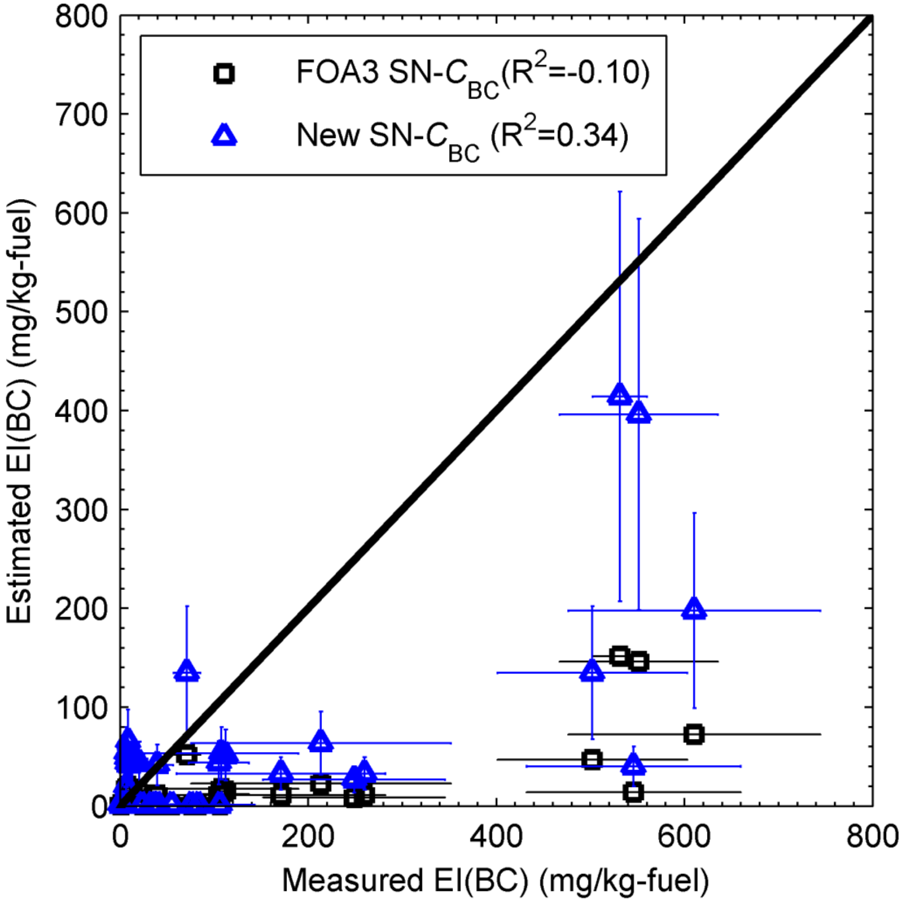
Validate estimated EI(BC)

- Current ICAO estimates are low
  - Greater than ×10 in 40% of cases
  - R^2 = -0.10
  - Consistent underestimation
  - Zero SN, non-zero EI(BC)



Validate estimated EI(BC)

- Current ICAO estimates are low
- New SN-C_{BC} improves but still inaccurate
  - $R^2 = 0.35$
- Remaining questions on reliability of certification SN
  - Engine degradation (?)
  - Sample line loss



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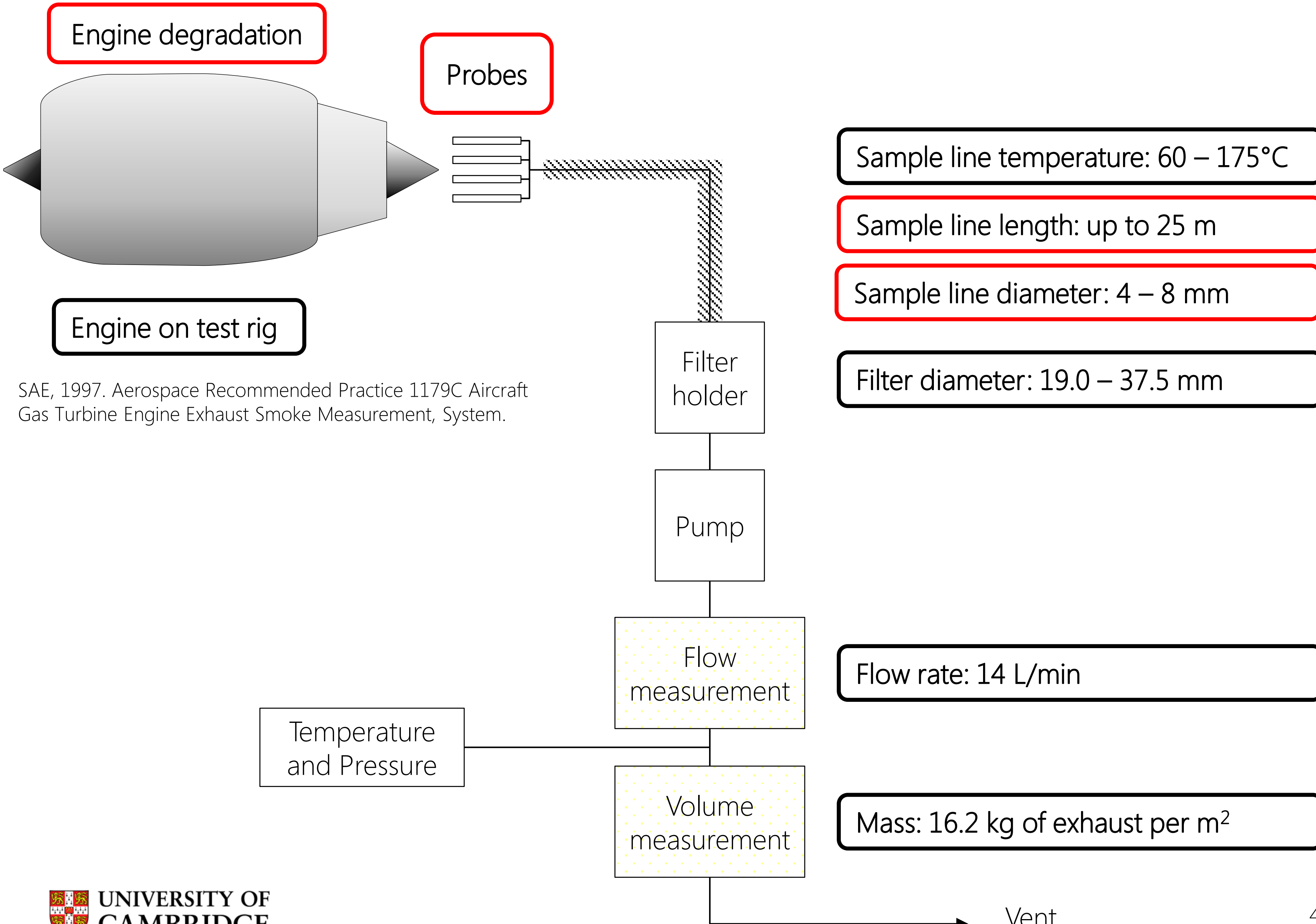
Remaining uncertainties



SAE, 1997. Aerospace Recommended Practice 1179C Aircraft Gas Turbine Engine Exhaust Smoke Measurement, System.

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Estimating EI(BC) without SN - FOX

$$C_{\mathrm{BC}}\left[\frac{\mathrm{mg}}{\mathrm{m}^3}\right] \approx \dot{m}_f \left(\underbrace{A_{form}\, e^{\left(-\frac{6390}{T_{fl}}\right)}}_{\text{Formation}} - \underbrace{\mathrm{AFR}\, A_{ox}\, e^{\left(-\frac{19778}{T_{fl}}\right)}}_{\text{Oxidation}} \right)$$

- Based on Arrhenius model for soot formation and oxidation
- Empirical – use measurements to calibrate
- More accurate estimates of EI(BC) at ground and cruise altitude

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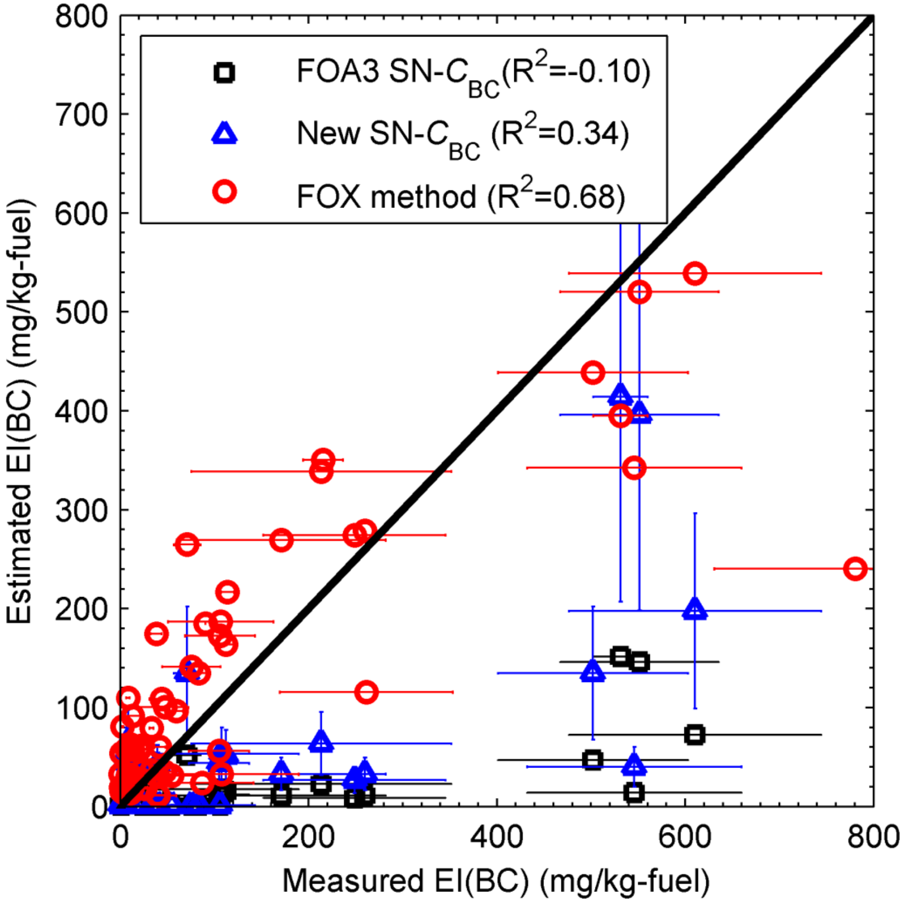
Estimating EI(BC) without SN

- FOA3: R^2 = 0=-0.10
- New SN-C_{BC}: R^2 = 0.34
- FOX method: R^2 = 0.68



EI(BC) at cruise

- FOX estimates agree within measurement error
- SULFUR 1-7 measurements
  - Cited as typical emissions values
  - Conducted at low airspeed
  - Low aircraft weight

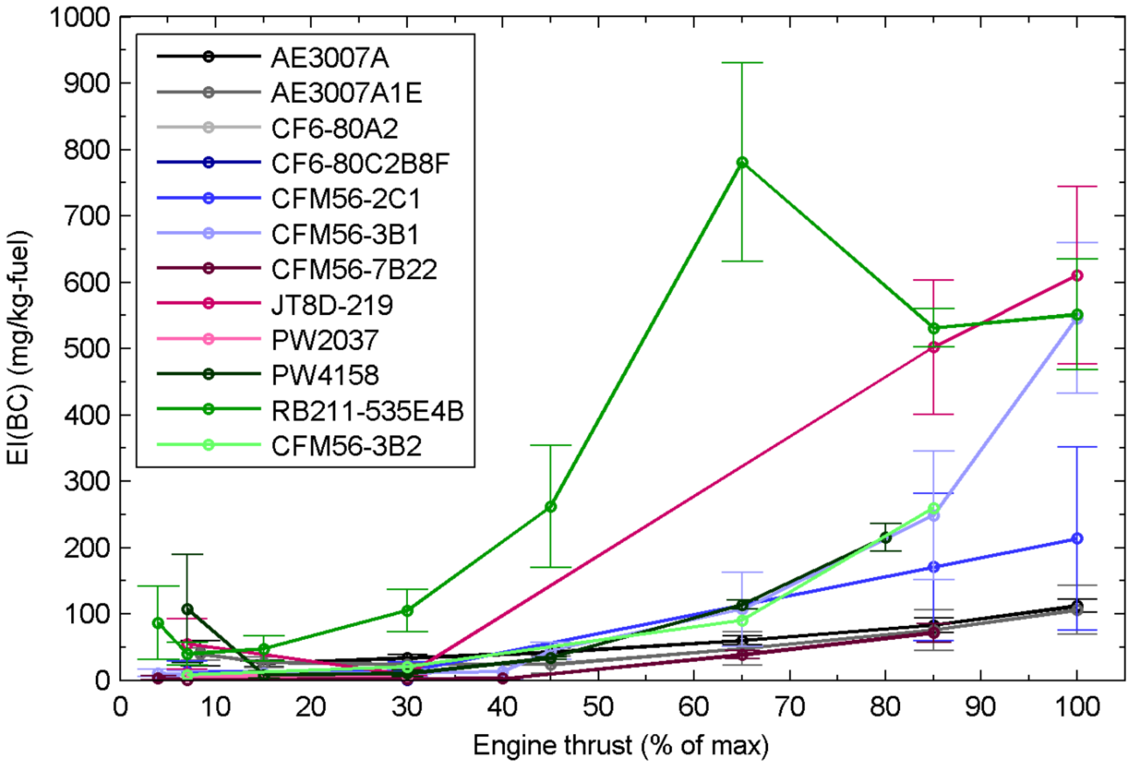
  → Low engine thrust setting (~20%)

SULFUR 1-7
(Schumann et al., 2002)

Schumann, U. et al. (2002) *JGR 107* (D15). doi:10.1029/2001JD000813

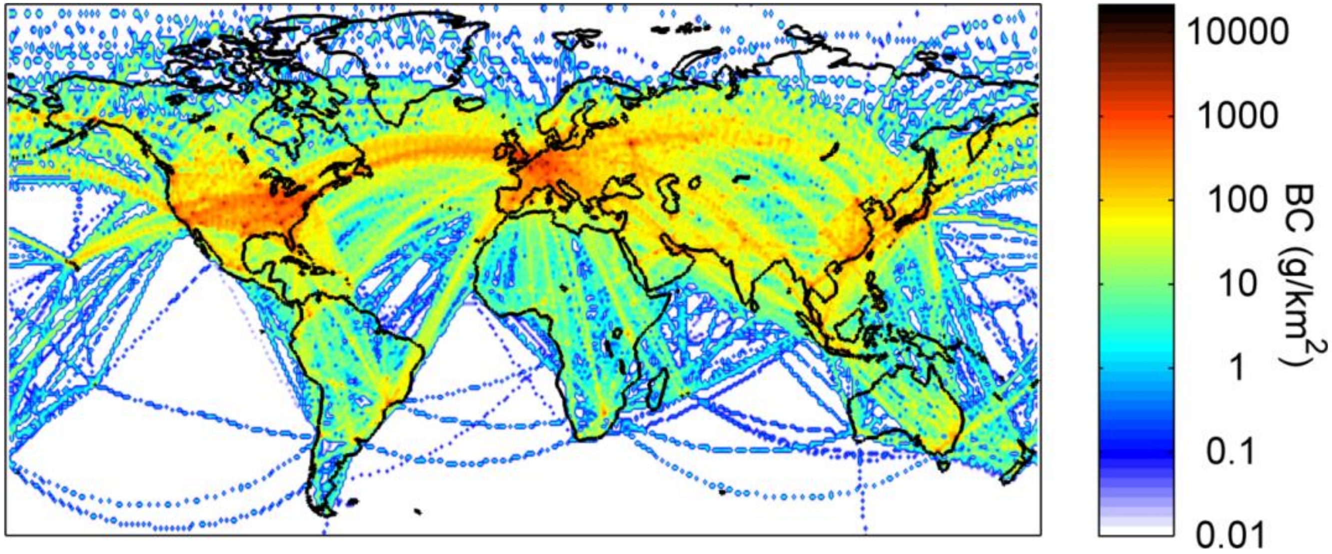
EI(BC) depends on engine thrust setting

- Ground level measurements indicate that EI(BC) increases with engine thrust setting



Global aircraft BC emissions

- ~2.5 higher than current best estimate used in climate impact evaluation
- Updated aviation direct BC RF is ~1/3 that of CO_2 (linear scaling)



Lee, D. S. et al. (2010) *Atmospheric Environment*, *44*(37), 4678–4734.

Summary

- SN reduced plume visibility
- Experiments to test SN-C_{BC} correlation
  - Controllable BC generation
  - Existing correlation underestimates by ×2.5 for 'aircraft-sized' BC particles
- Remaining SN uncertainty
  - Line losses
  - Probe design
  - Engine degradation

Summary

- Empirical BC emissions model independent of SN developed
- Updated estimate of global aircraft BC emissions
  - ~2.5 higher than previous estimates
  - Direct BC RF is ~1/3 that of CO_2
  - Greater importance of measures to reduce BC emissions
  - Need more measurements at cruise

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Acknowledgements

- Funding from EPSRC
- Cambustion Ltd. for loan of CPMA
- Cardiff University for loan of filter holders
- APEX 1-3 data: Aerodyne, MS&T
- SAMPLE III data: Cardiff University, Rolls Royce plc.

Thank you, questions?

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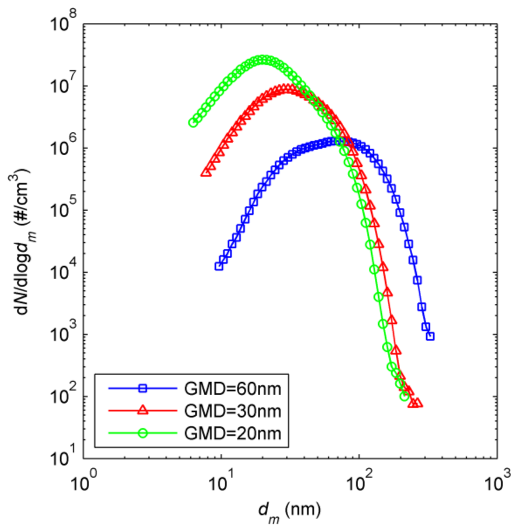
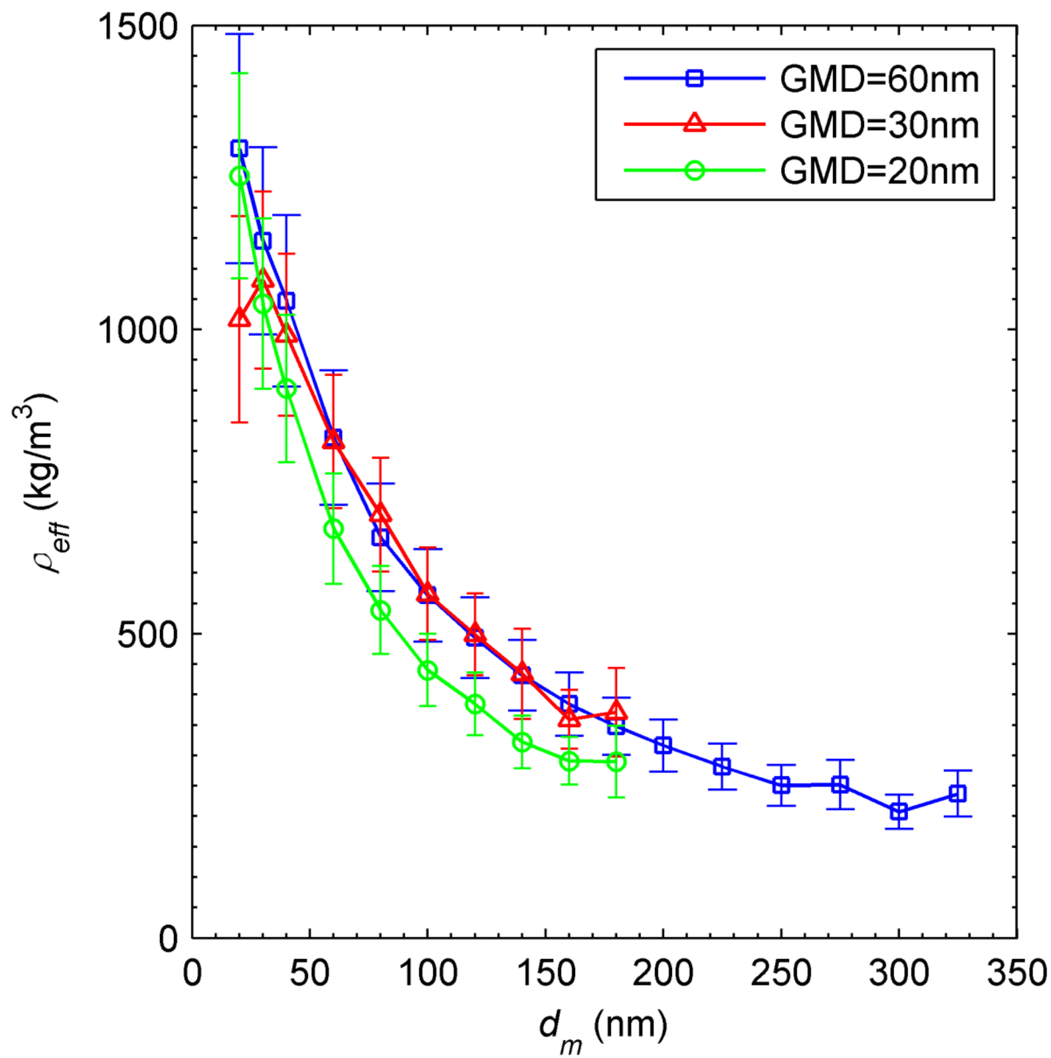
Effective density



$$\rho_{\mathrm{eff}} = \frac{m_p}{\frac{\pi}{6} d_m^3}$$

- Mass divided by volume of sphere with equal mobility diameter
- Material density ~1,800 kg/m^3



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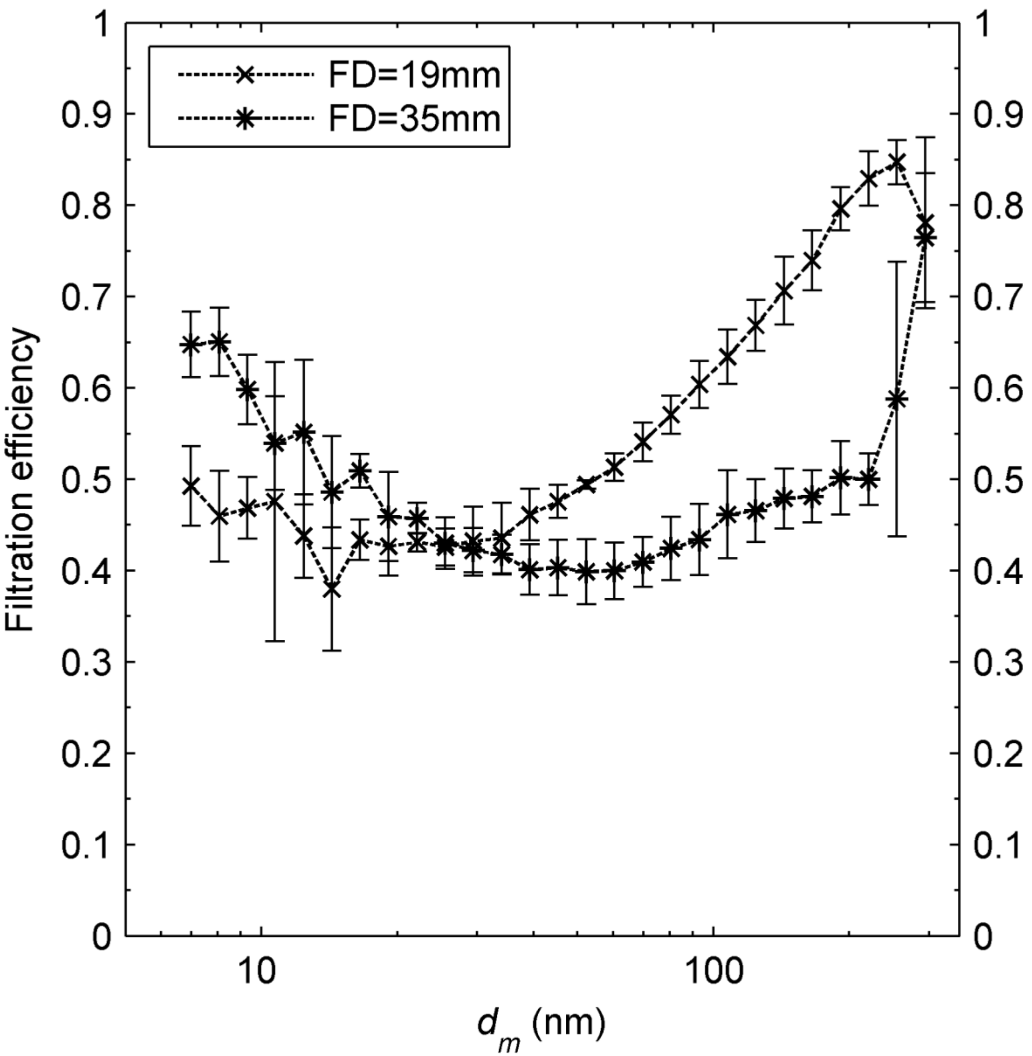
Filtration efficiency

- <u>Filtration efficiency is strongly dependent on particle mobility diameter</u>
- Significant difference for different filter diameters (FD)
- For FD = 19 mm
  - Minimum filtration
    - 40%
    - <30nm
- For FD = 35 mm
  - Minimum filtration
    - 40%
    - 40-60 nm



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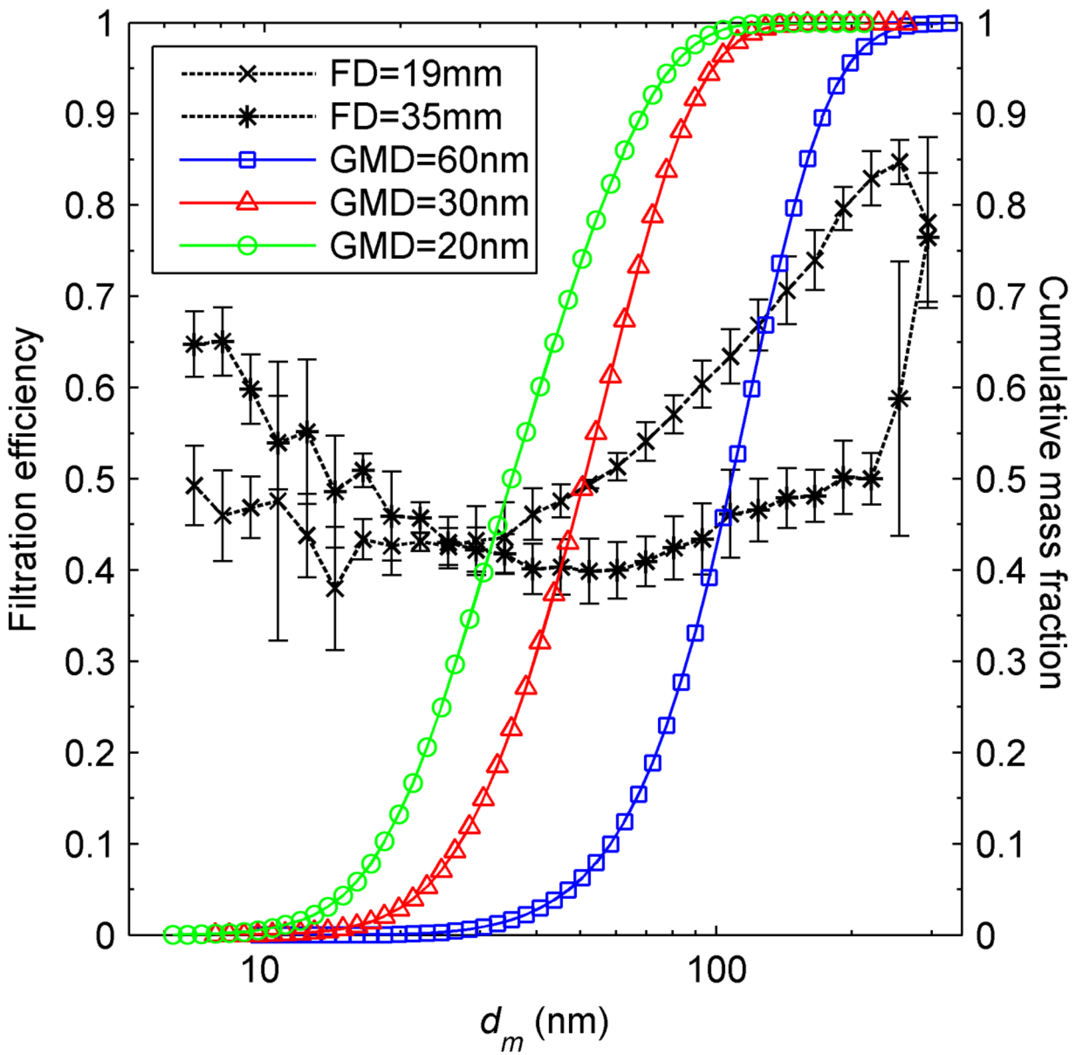
    - 40%
    - 40-60 nm
- Mass distributions indicate less mass collected for smaller GMD



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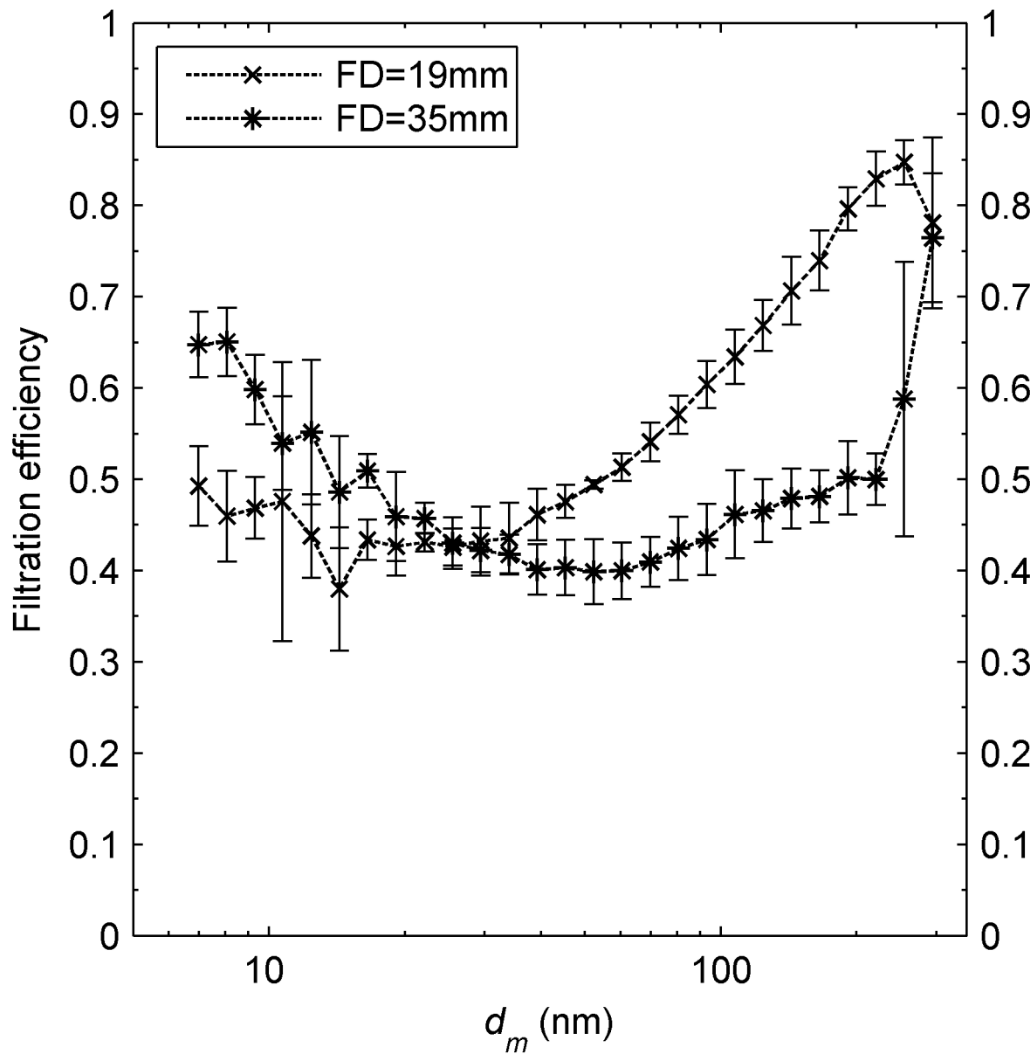
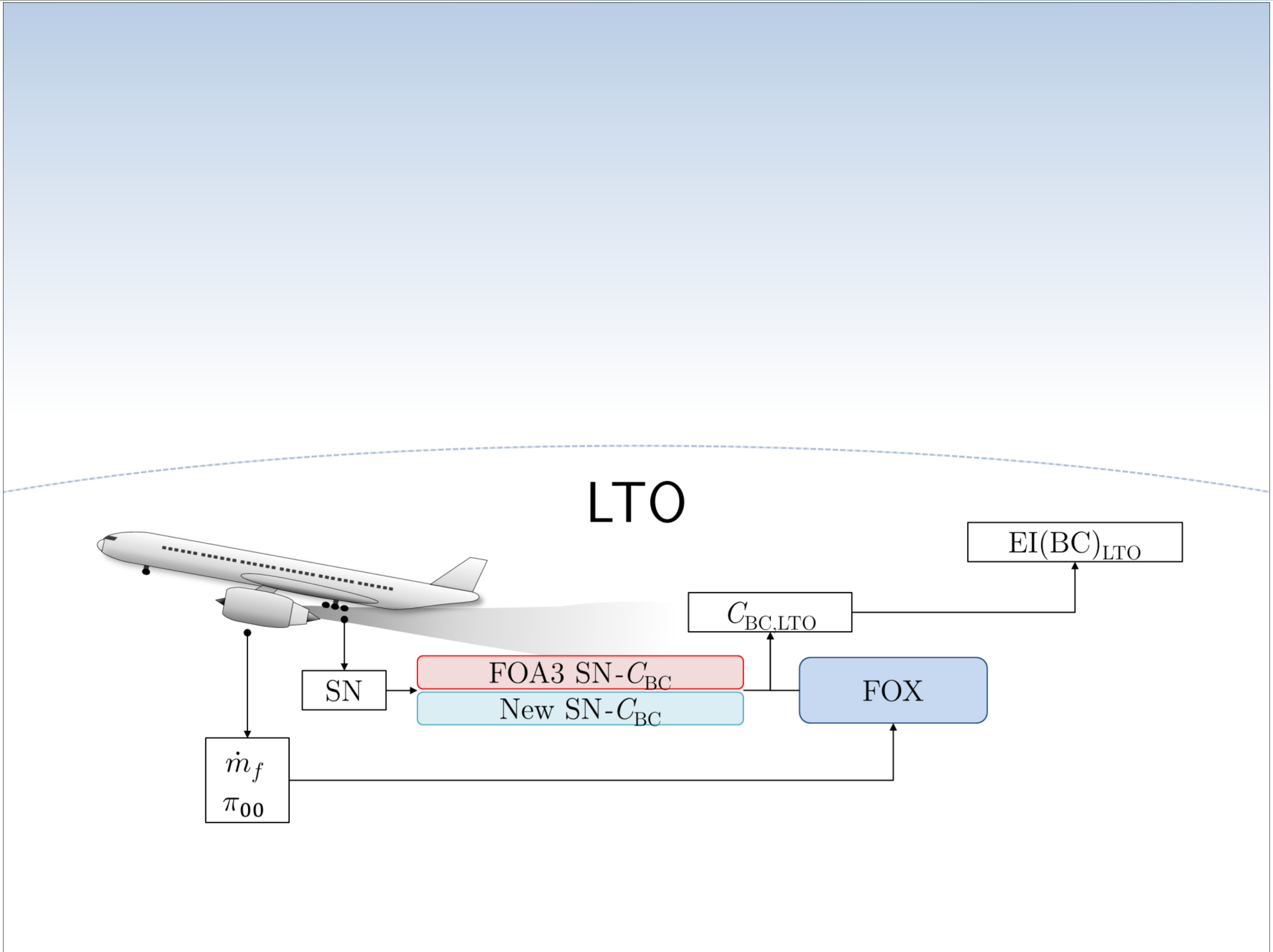
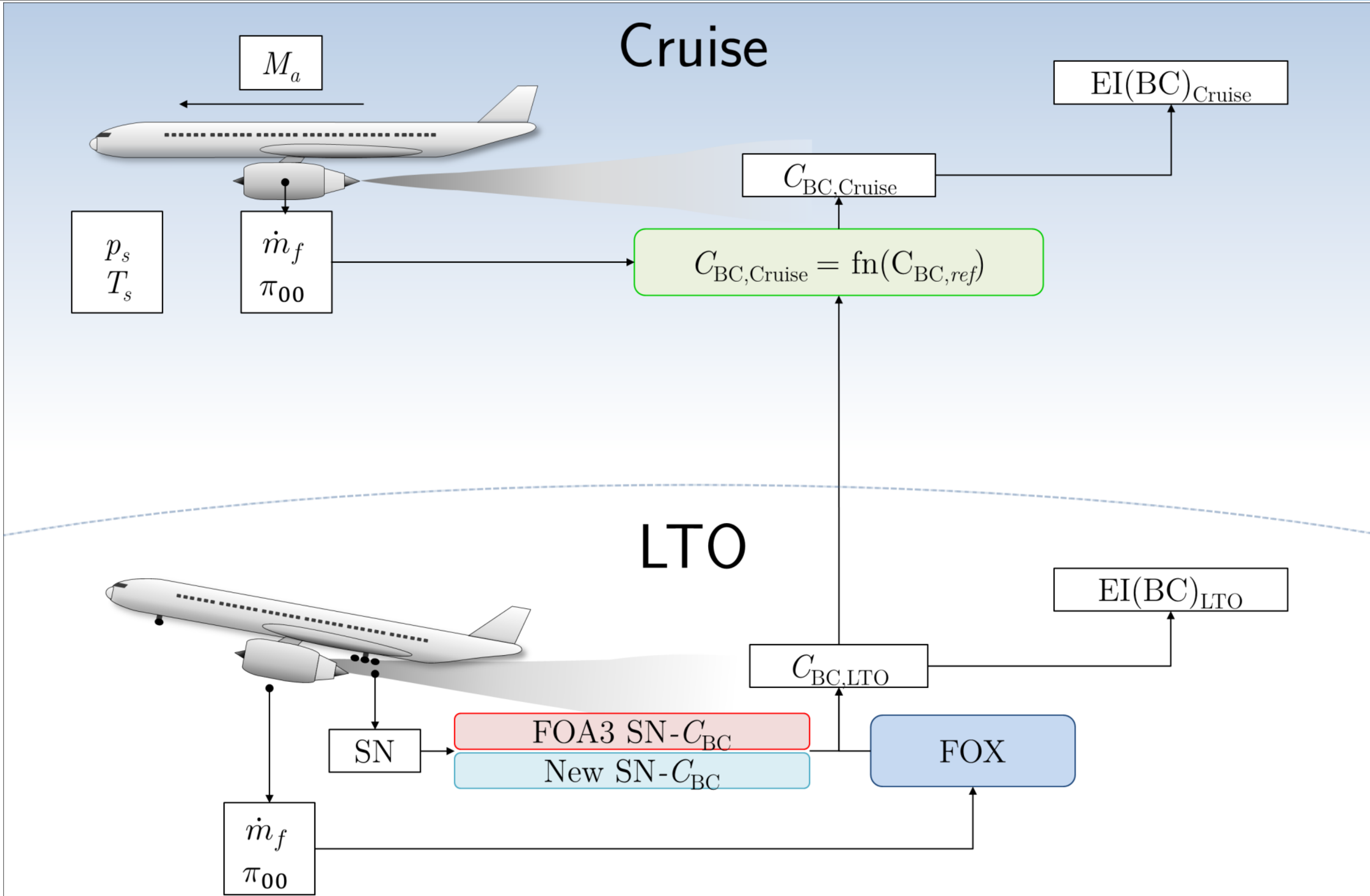


Global aircraft BC emissions

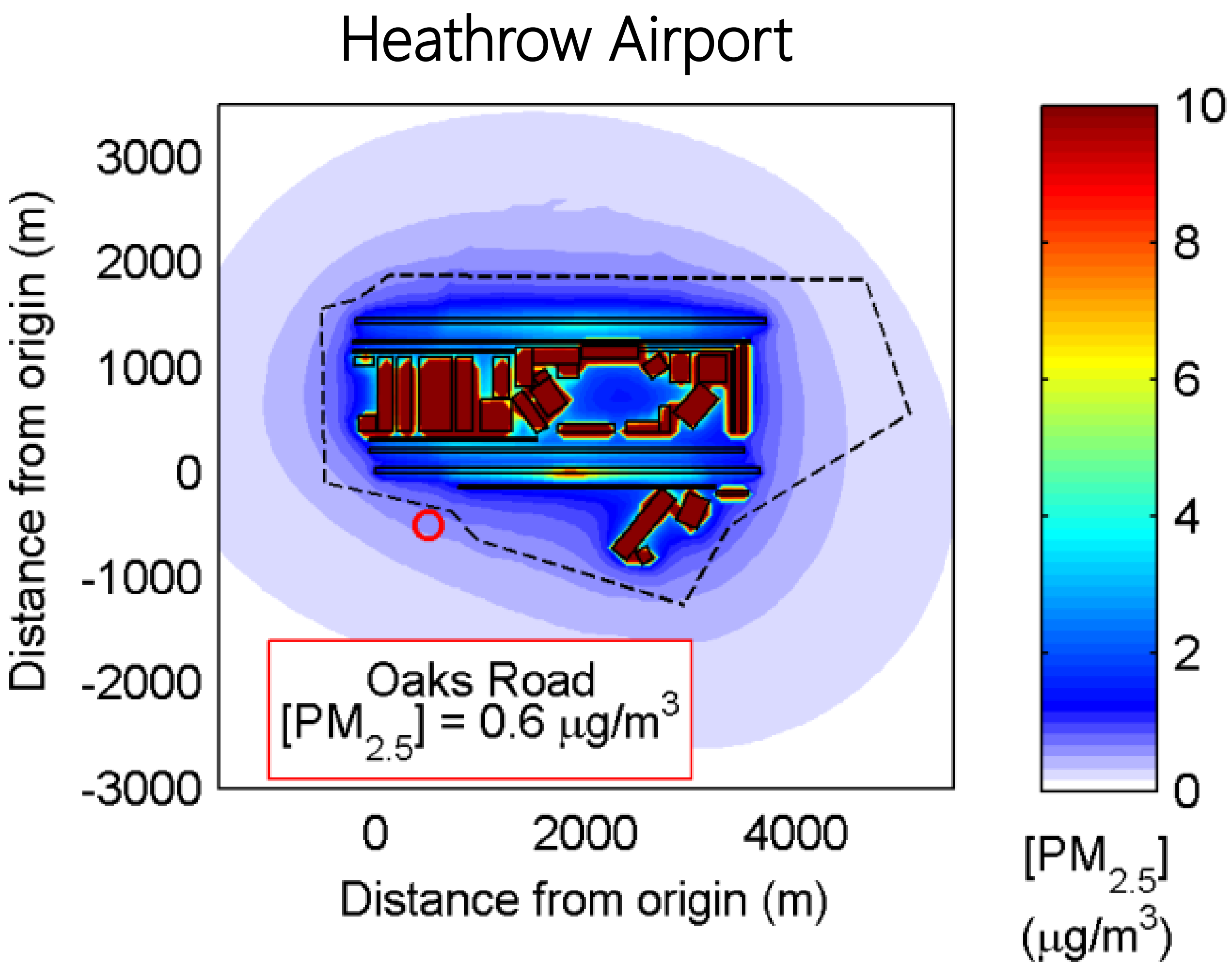


Global aircraft BC emissions



Döpelheuer, A., & Lecht, M. (1998). *RTO AVT Symposium on Gas Turbine Engine Combustion Emissions and Alternative Fuels* (p. RTO MP–14). Lisbon, Portugal.

Outcomes – Airport air quality



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Validation of cruise EI(BC) estimates

- SULFUR 1-7 measurements

Schumann et al. (2002)

Aircraft Engine	A310-300 CF6-80C2A2	B737-300 CFM56-3B1	A340 CFM56-5C4
$\dot{m}_f / \dot{m}_{f,max}$ (%)	18.6	22.5	20.0
Measured EI(BC) (g/kg-fuel)	0.019 ± 0.01	0.011 ± 0.005	0.010 ± 0.003
Estimated EI(BC) FOX (g/kg-fuel)	0.017	0.015	0.011

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Schumann, U. et al. (2002) *JGR 107* (D15). doi:10.1029/2001JD000813

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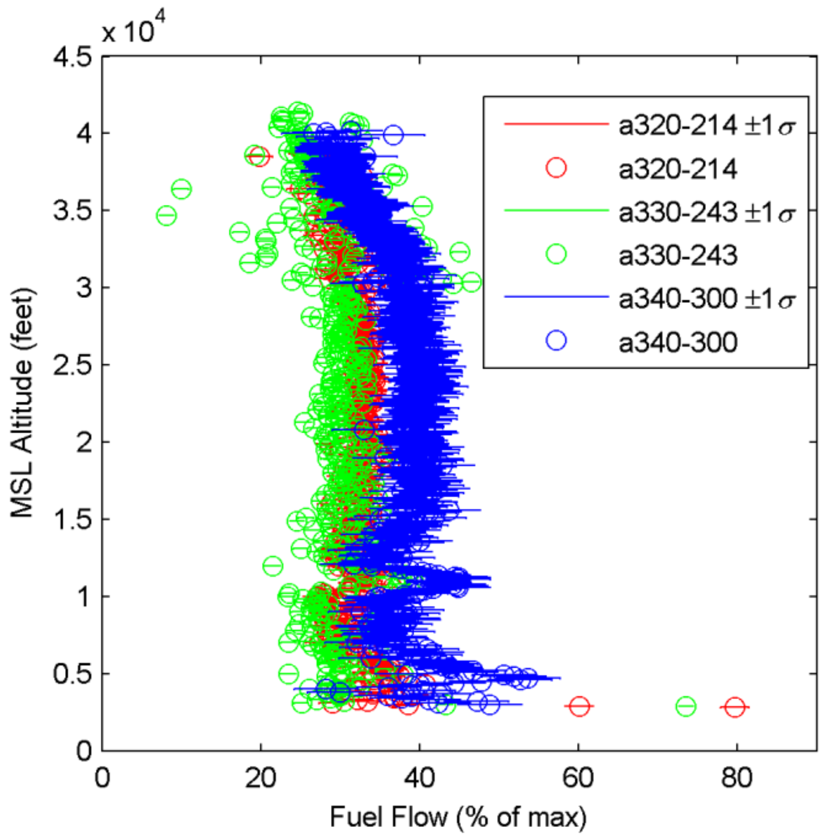
Engine thrust setting at cruise

- Real flight data from Flight Data Recorder



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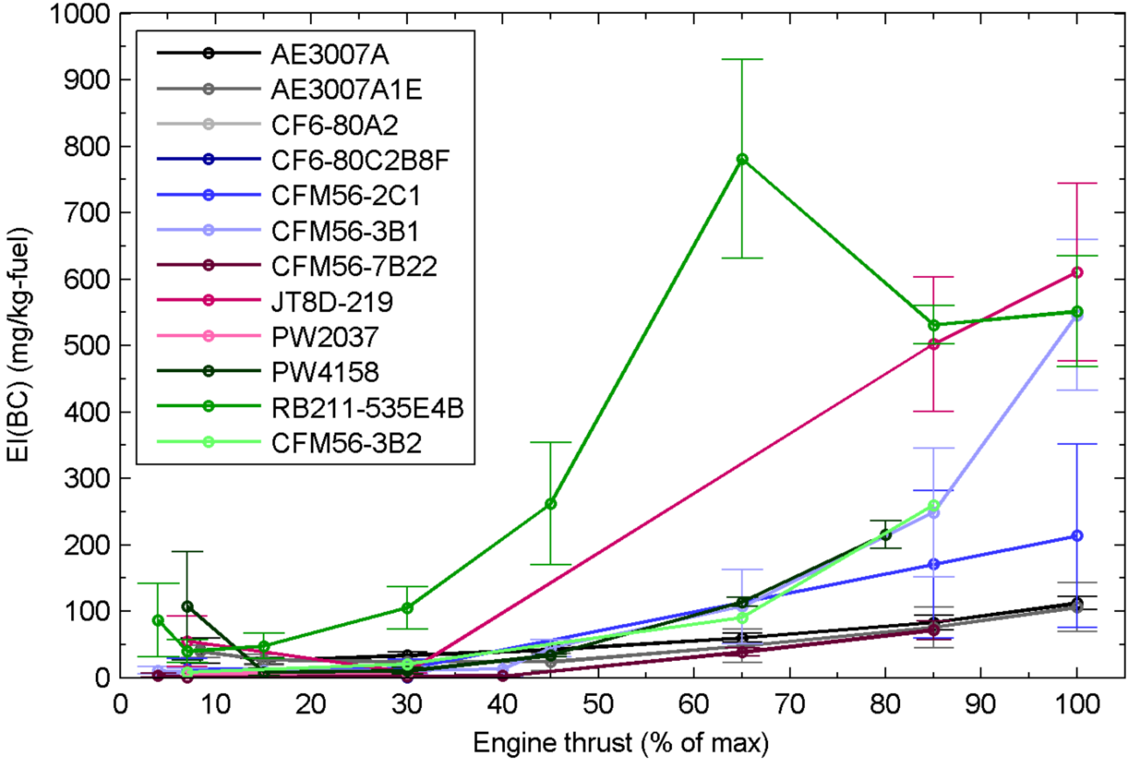
EI(BC) depends on engine thrust setting

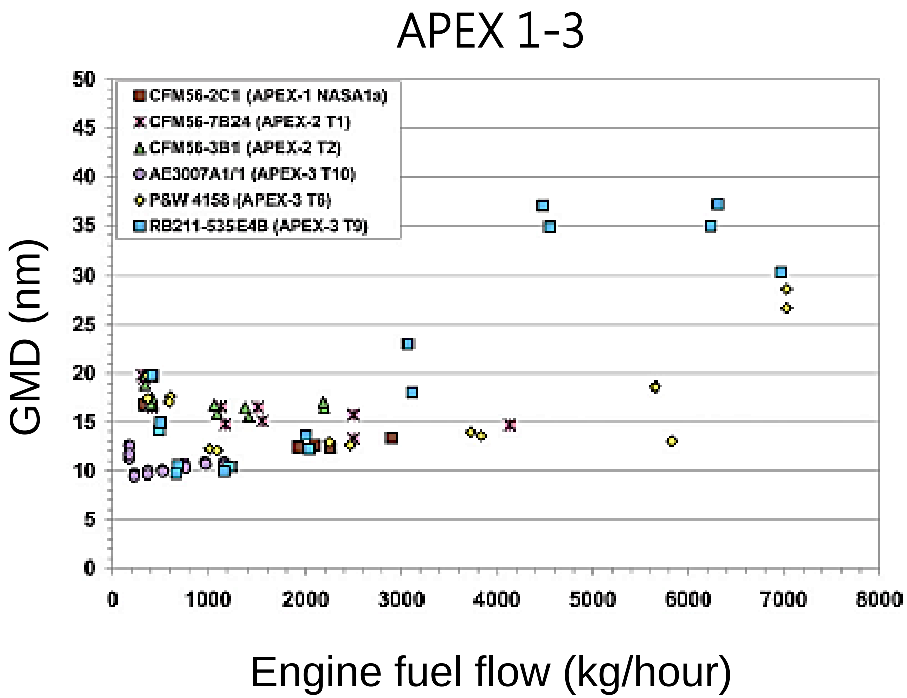


Motivation

- Aircraft gas turbine engines emit PM
  - Non-volatile black carbon (BC)
  - Semi-volatile organic material and sulphates
- Degrade of air quality and contribute to radiative forcing
- Current SN regulation concerned with plume visibility
- Limited data on aircraft BC mass emissions
- Engines lifetimes of ~decades and new non-volatile particle number, size and mass (SAE E-31) standards unlikely to be applied to engines currently in service

SN to BC mass concentration

- Correlation is inconsistent with measured aircraft PSDs (GMD = 20-40 nm)



Source: Kinsey, J. S. et al., 2010. *Atmospheric Environment*, *44*(17), 2147-2156.

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SN to BC mass concentration

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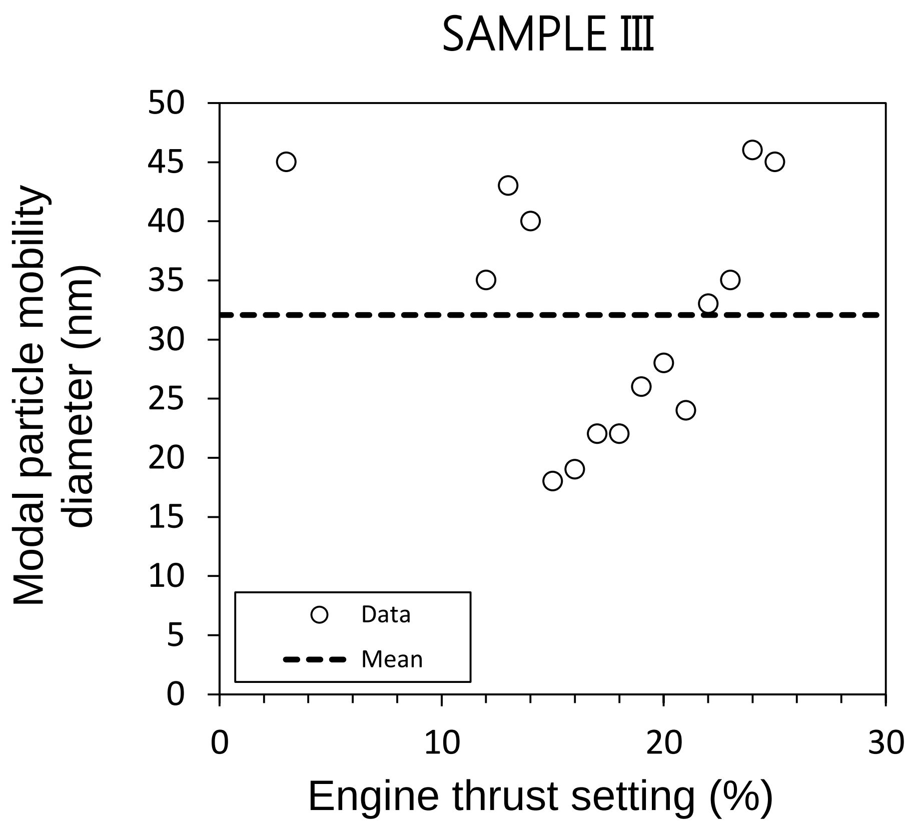

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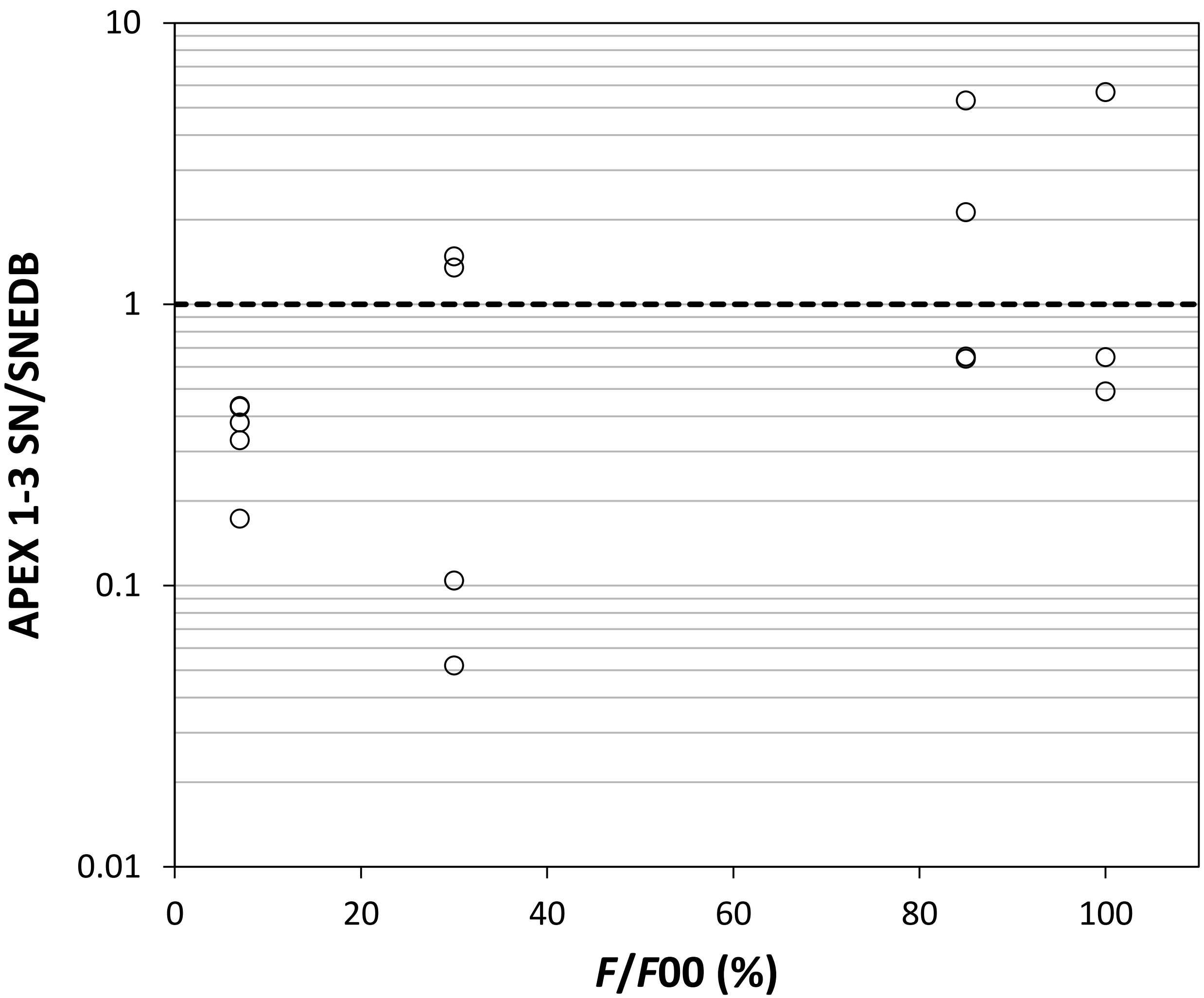
SN changes over time



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SN to BC emissions index – FOA3

- Estimate <u>BC emissions index</u> (mass per unit of fuel burned) from the SN

$$\mathrm{EI(BC)} = C_{\mathrm{BC}}(\mathrm{SN}) \times Q$$

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SN

- **Regulatory measurement**
- Standard procedure (ARP 1179C)

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$$\mathrm{EI(BC)} = C_{\mathrm{BC}}(\mathrm{SN}) \times Q$$

C_{BC}

- mg/m^3
- Empirical correlation between SN and C_{BC}

SN

- Regulatory measurement
- Standard procedure (ARP 1179C)

SN to BC emissions index – FOA3

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SN
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- Standard procedure (ARP 1179C)

Q
- m^3/kg-fuel
- Volumetric exhaust flow rate

SN to BC emissions index

- **BC emissions index**: mass per unit of fuel burned

$$\mathrm{EI(BC)} = C_{\mathrm{BC}}(\mathrm{SN}) \times Q$$

EI(BC)

- mg/kg-fuel
- Standard metric

C_{BC}

- mg/m^3
- Empirical correlation between SN and C_{BC}
- Sources of error:
  i. SN measurement variability
  ii. Particle size distribution

Q

- m^3/kg-fuel
- Volumetric exhaust flow rate
- ±30% uncertainty

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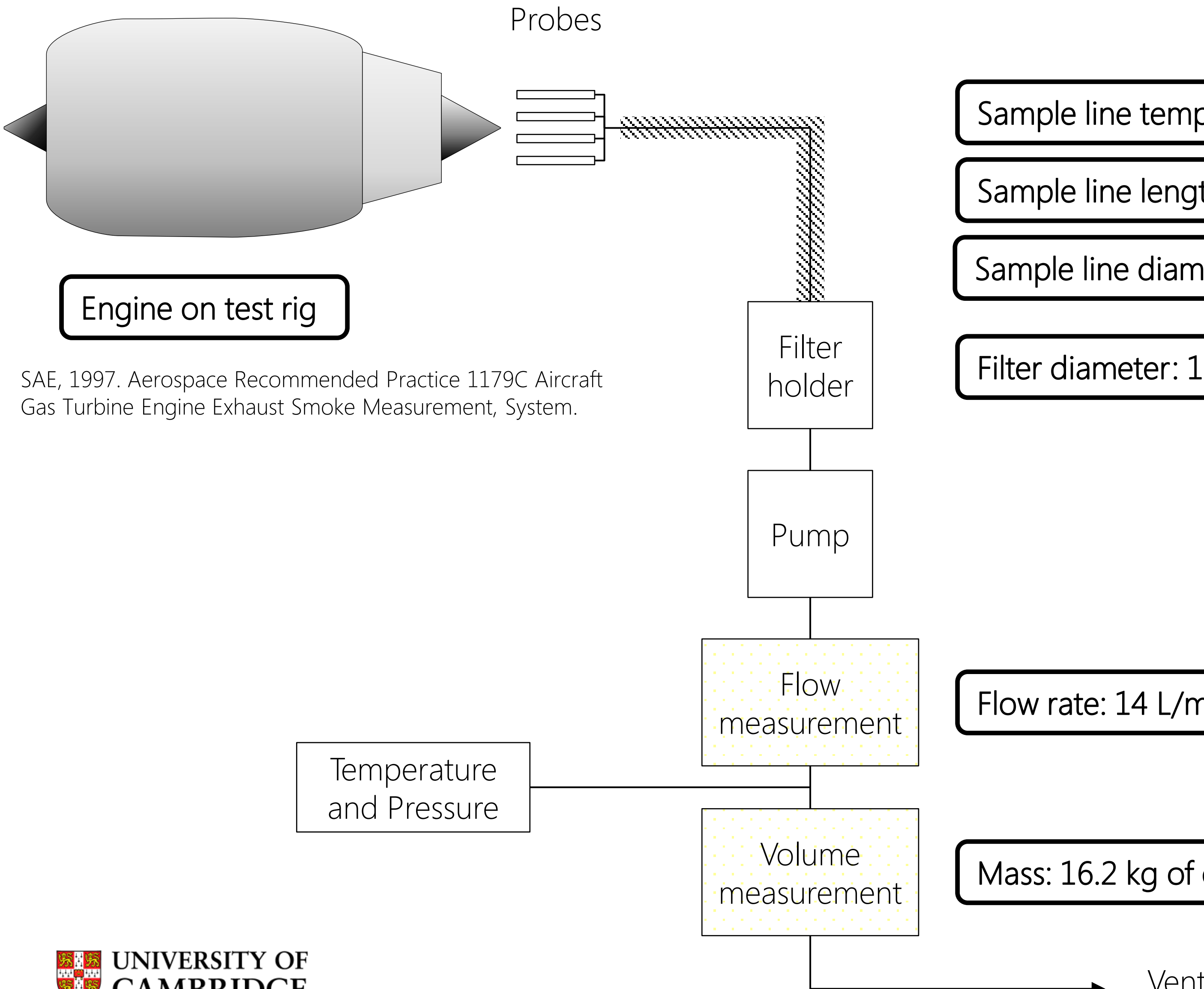
Gravimetric analysis

Burner Setting	Collected mass (mg)	$C_{BC,grav}$ (µg/m^3)	$C_{BC,peff}$ (µg/m^3)	$C_{BC,grav}/C_{BC,peff}$
GMD=60nm	0.41-0.43 (±0.02)	161-167 (±8)	174-184 (±15)	0.90-0.93
GMD=20nm	0.31-0.66 (±0.02)	123-128 (±8)	125-140 (±16)	0.91-0.98

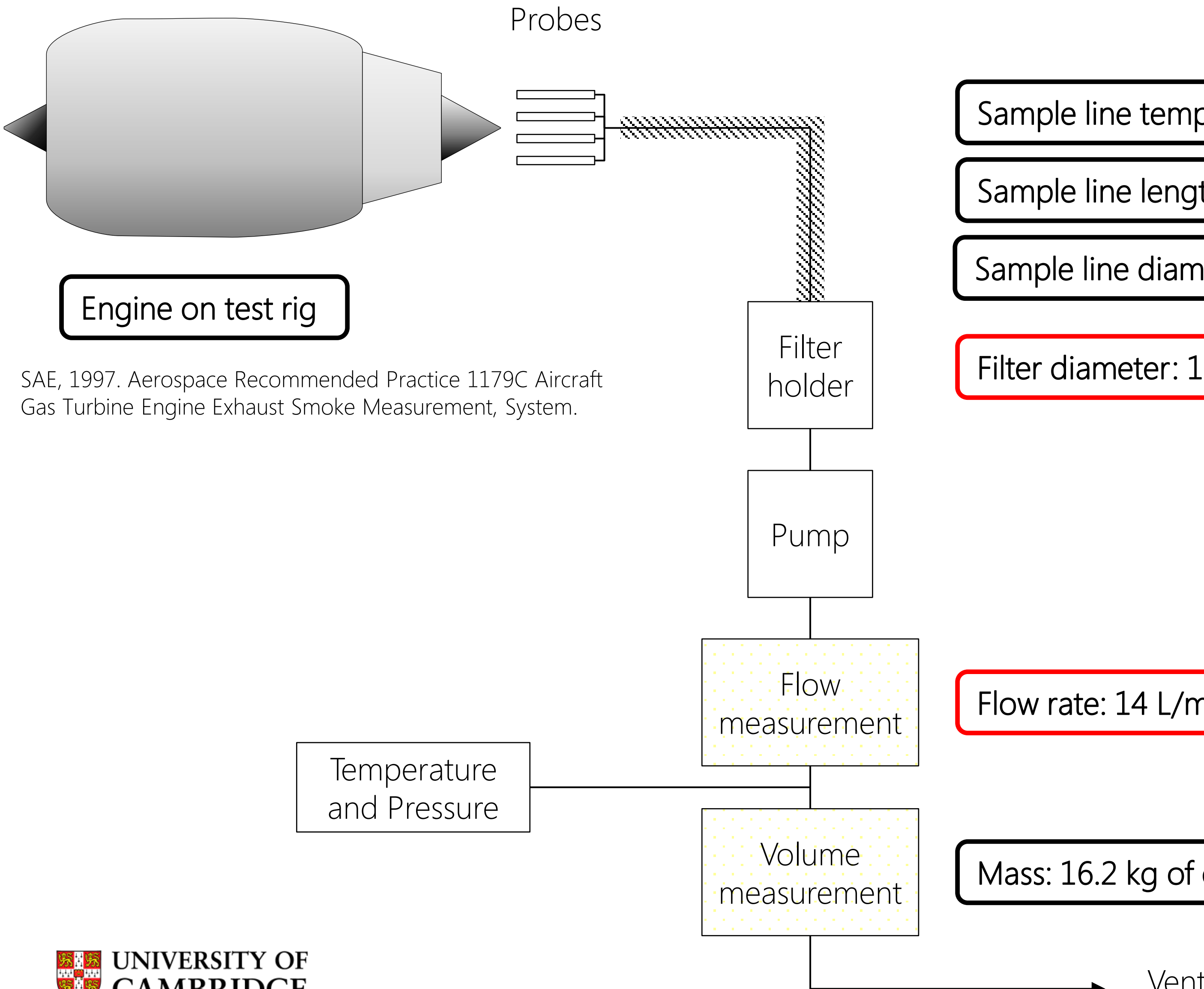
(ii) SN measurement variability



SAE, 1997. Aerospace Recommended Practice 1179C Aircraft Gas Turbine Engine Exhaust Smoke Measurement, System.

- Sample line temperature: 60 – 175°C
- Sample line length: up to 25 m
- Sample line diameter: 4 – 8 mm
- Filter diameter: 19.0 – 37.5 mm
- Flow rate: 14 L/min
- Mass: 16.2 kg of exhaust per m^2

(ii) SN measurement variability



Engine on test rig

SAE, 1997. Aerospace Recommended Practice 1179C Aircraft Gas Turbine Engine Exhaust Smoke Measurement, System.

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Sample line diameter: 4 – 8 mm

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Mass: 16.2 kg of exhaust per m^2

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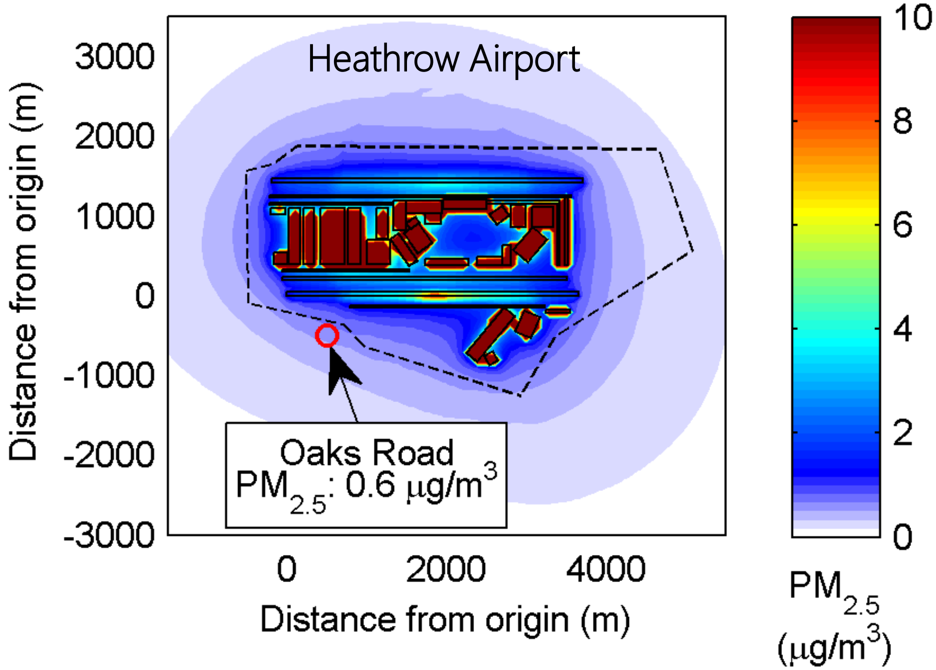
SN to estimate aircraft BC emissions

- First Order Approximation v3 method (FOA3)
- Developed in International Civil Aviation Organization CAEP meetings
- Estimate BC emissions during landing and take-off



ICAO, 2011. Airport Air Quality Guidance Manual.
Wayson, R. et al. (2009). *J Air & Waste Management Association*, *59*(1), 91–100.
Yim, S.H.L. et al. (2013). Atmospheric Environment 67, 184–192.