Particle Effective Density Measurements: Alternative Approaches

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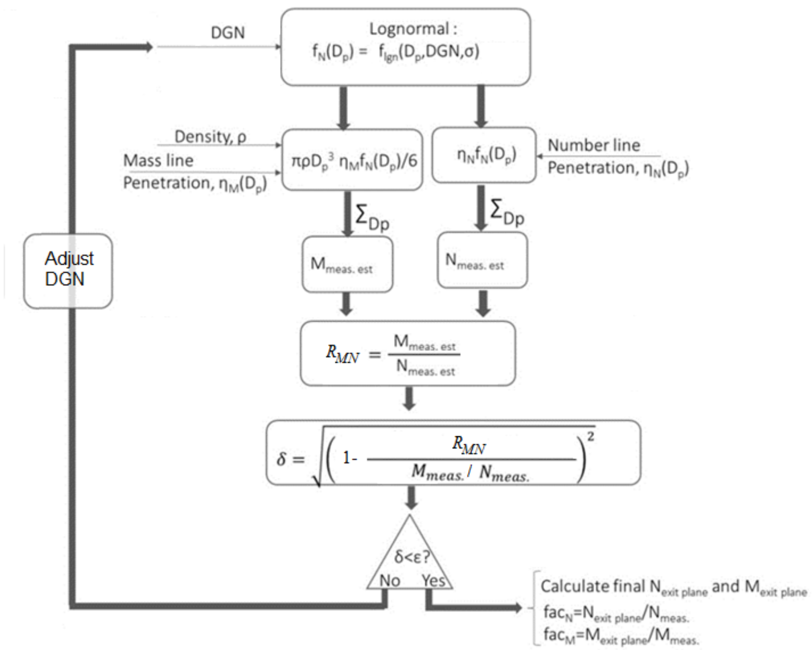
Motivation

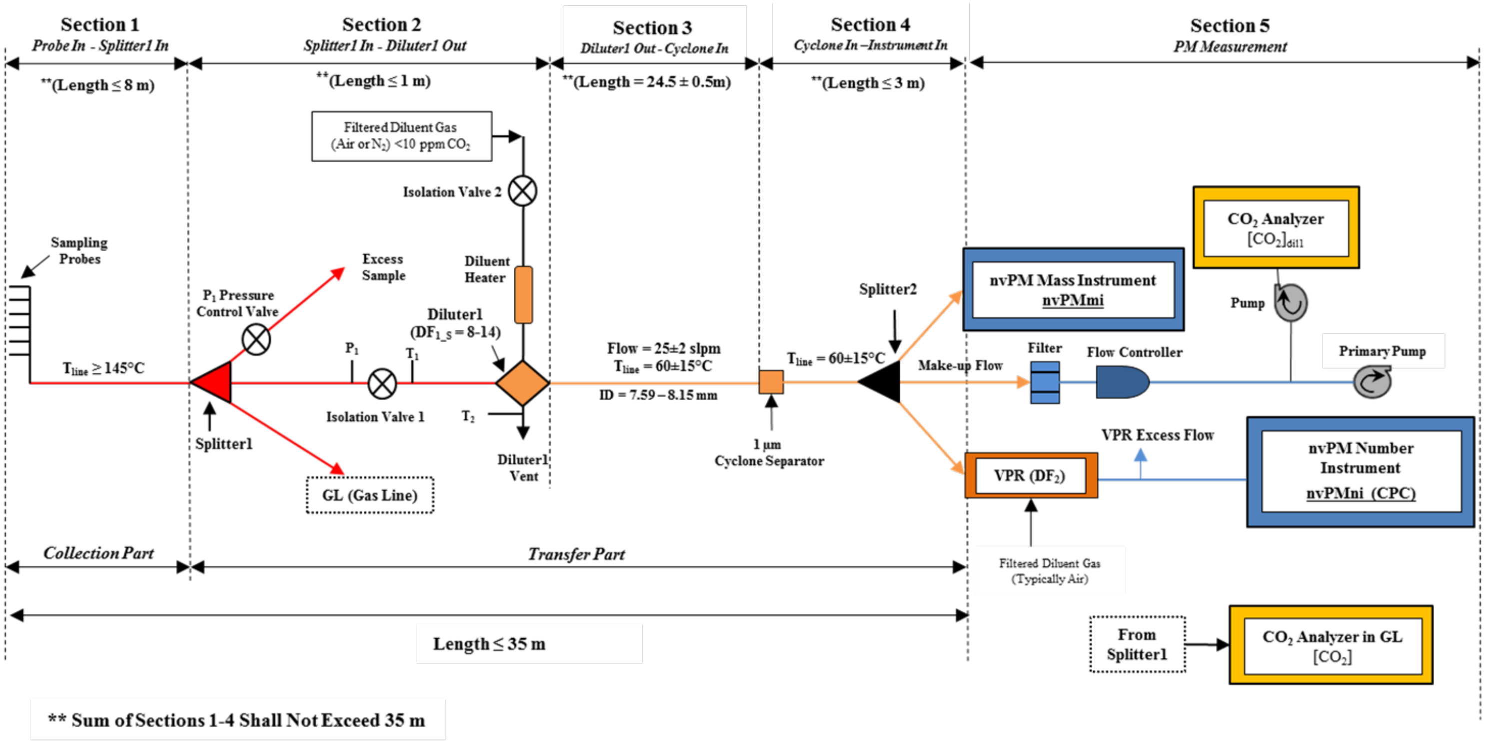
- New standards on aircraft emissions being developed including
  - CO_2
  - Solid particle mass
  - Solid particle number larger than 10 nm
- Extreme exhaust sampling conditions require very sampling lines
- Must correct for particle losses in the sampling system which may be severe, 80-90% loss at 10 nm
- Here I am examining a critical assumption of the line loss method, known particle density

Line loss correction method



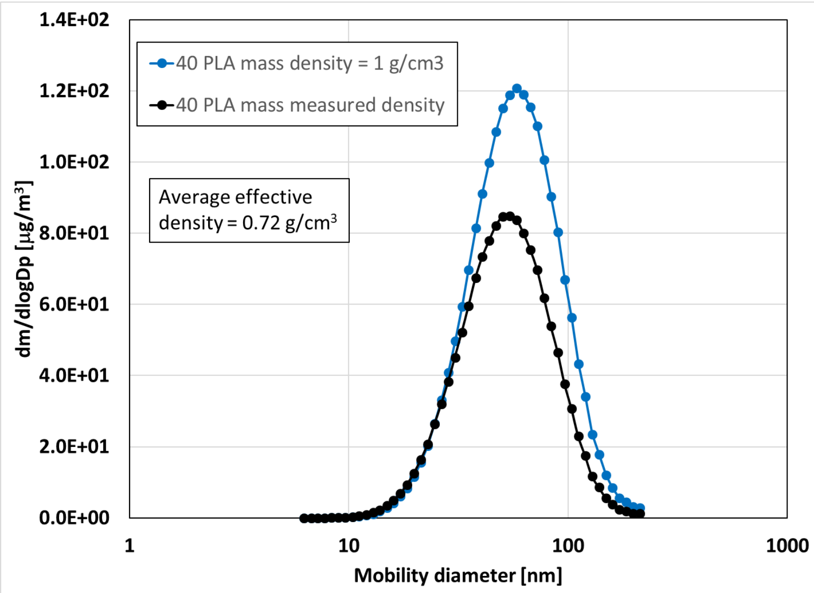
- Size dependent corrections are required but the SAE E-31 committee decided against direct particle size measurement
- **The only measurements available are nonvolatile particle mass and number (nvPM and nvPN)**
- Requires well validated line loss model, currently uses UTRC model
- Assumptions
  - No nucleation or coagulation
  - Engine exit plane size distribution is **lognormal**
  - **Effective particle density** and σ_g are known
  - Remaining unknown is the exit plane geometric mean diameter
  - Geometric mean diameter is varied in an iterative solution until the exit plane distribution, before line losses yields the observed downstream nvPM and nvPN

Typical aircraft exhaust sampling system



SAE International Aerospace Information Report 6241

Impact of density on line loss correction factors



Impact of density on estimated line loss correction factors, K_n for number and K_m for mass

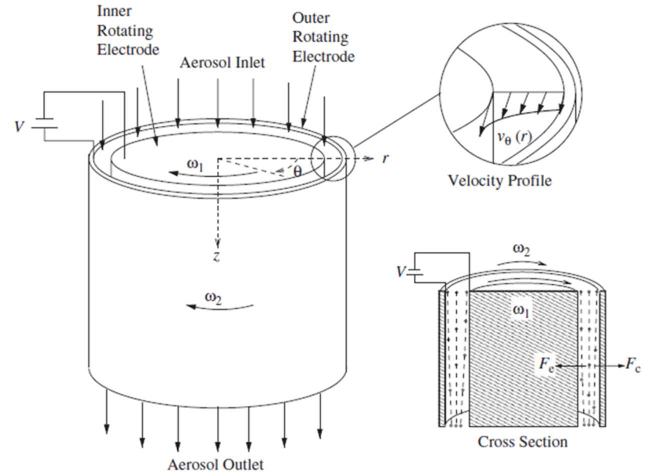
Density g/cm³	K_n	K_m
1.0	6.8	1.5
0.72	5.59	1.42
% Error	22	6

Approach

For each combustion source particle properties were varied by

- Changing load
- Changing fuel
- Using a catalytic stripper (CS) to remove adsorbed semivolatile matter and separate semivolatile particles
  - CS operated at 350 C, some material tightly bound to particles may remain
  - Particles measured downstream of CS are defined as "solid" particles
- Concentration varied over wide range by varying dilution ratio

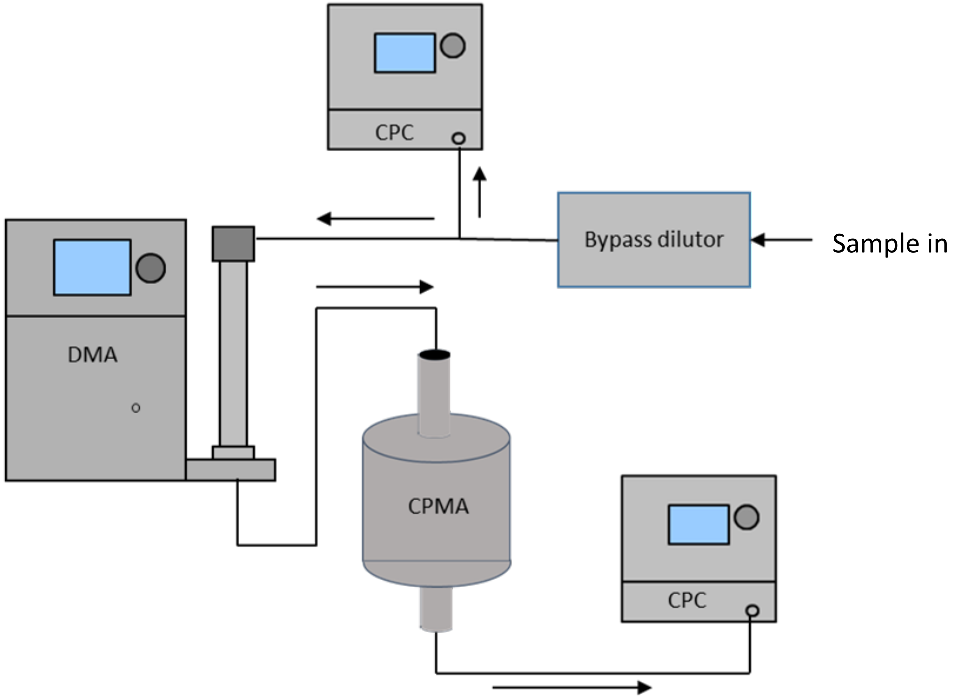
Density measurements
Setup typically used and used in VARIAnT 3
DMA-CPMA-CPC



$$mr\omega^2 = qE = \frac{N_q eV}{r\ln\left\{{}^{r_o}/_{r_i}\right\}}$$

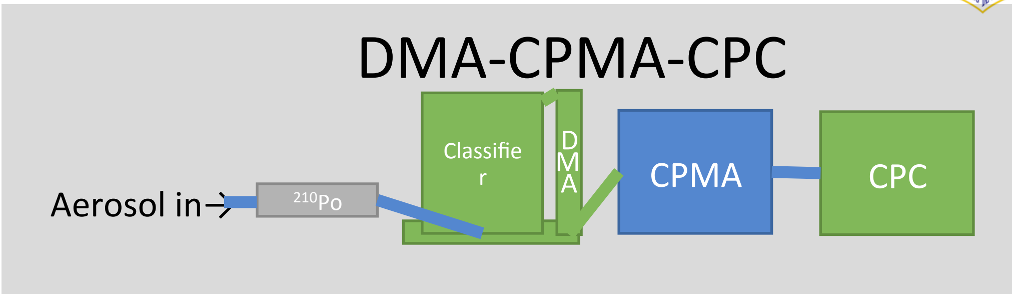
$$\frac{m}{N_q} = \frac{eV}{r^2\omega^2\ln\left\{{}^{r_o}/_{r_i}\right\}}$$

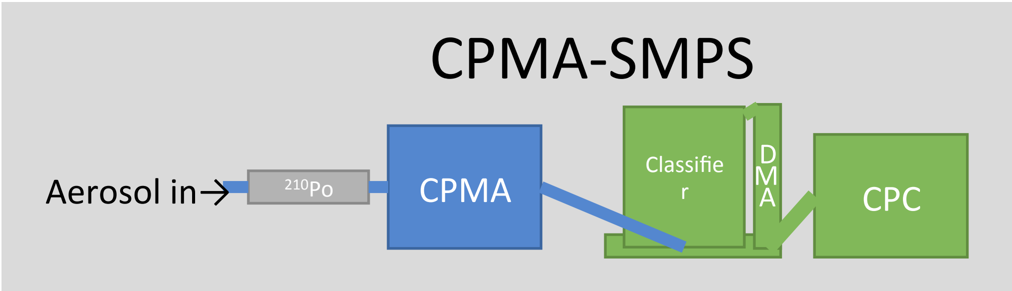
Adapted from Olfert, et al., JAS 37 (2006) 1840-1852



Measuring density in two ways in VARIAnT 4

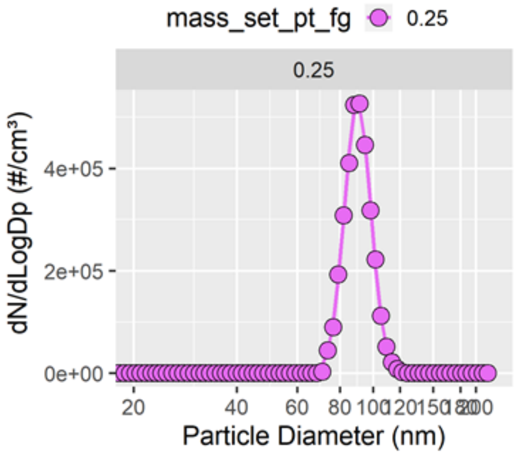
- Data was taken 2 distinct measurement configurations
- Each configuration had a ^{210}Po neutralizer before instruments
- DMA-CPMA-CPC
  - Use DMA to select a single electrical mobility diameter
  - Scan over range of masses to produce a mass distribution
- CPMA-DMA-CPC
  - Use CPMA to select a single mass to charge ratio
  - Perform a typical SMPS scan (DMA-CPC) over range of electrical mobility diameters
  - Much faster





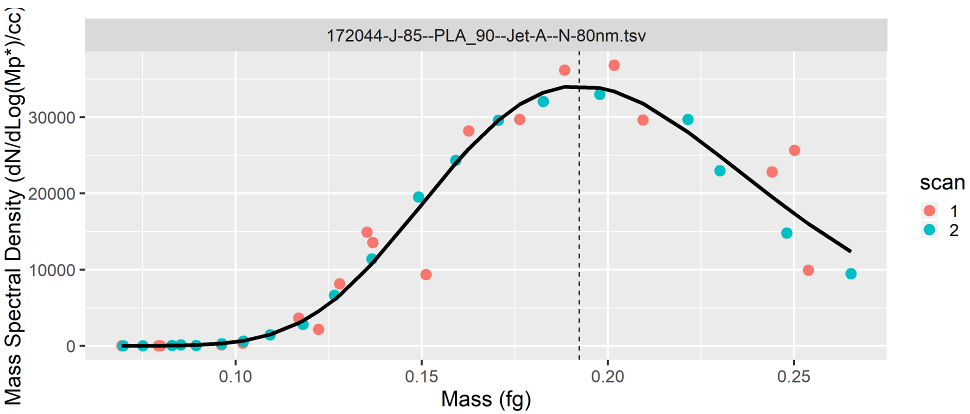
Examples of single data point for each configuration

CPMA-DMA-CPC



- Solid line represents best fit of lognormal to data

DMA-CPMA-CPC



- Each DMA set point had and "up" and a "down" scan
- Solid black line represents fit to both scans
- Dashed vertical line represents geometric mean diameter from a lognormal fit

Computing effective density from data

CPMA-SMPS

- Fit mass selected SMPS scan to lognormal
- Use geometric mean diameter from fit, $GMD_{SMPSfit}$
- $\rho = \frac{6\, mass_{setpoint}}{\pi\, GMD_{SMPSfit}^{3}}$

DMA-CPMA-CPC

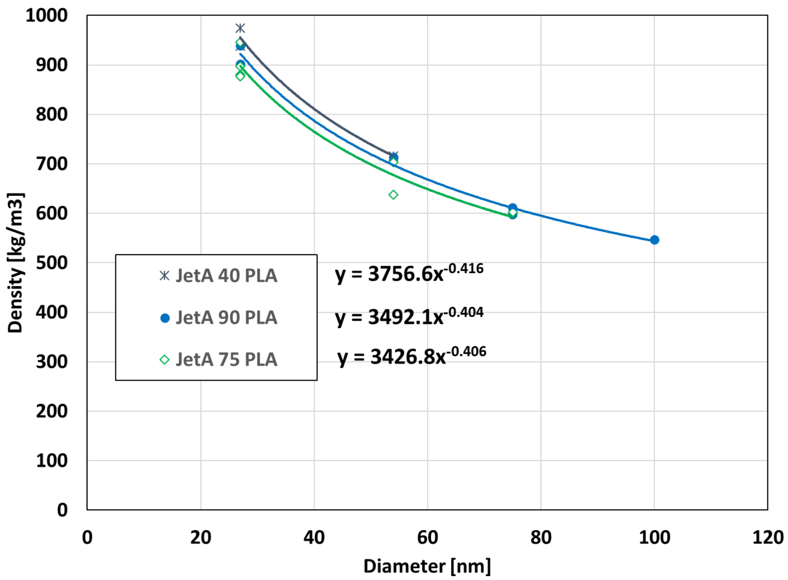
- Fit DMA particle diameter selected CPMA scan to lognormal
- Use geometric mean diameter from fit, $GMD_{massfit}$
- $\rho = \frac{6\, GMD_{massfit}}{\pi\, DMA_{setpoint}^{3}}$

VARIAnT 3 measurements

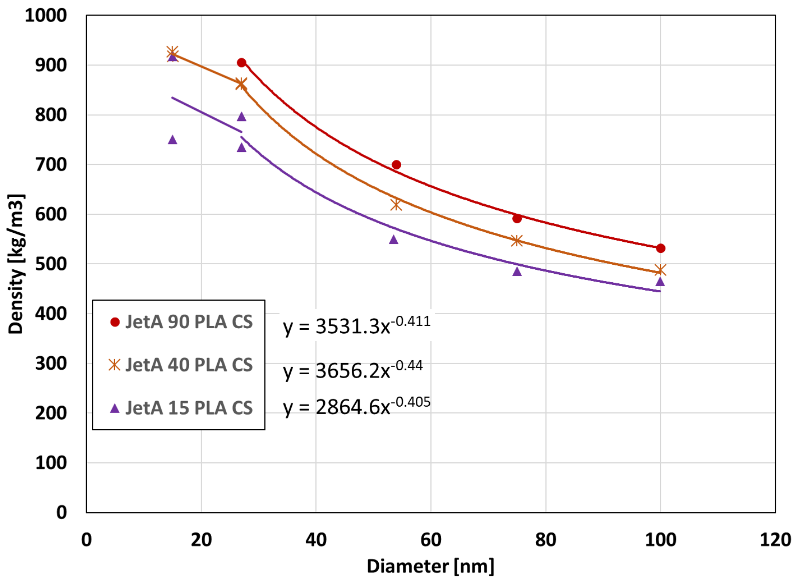
- All measurements used DMA-CPMA-CPC
- Selected results below

J-85 turbojet tests – influence of engine load (10 PLA = idle, 90 PLA = max thrust)

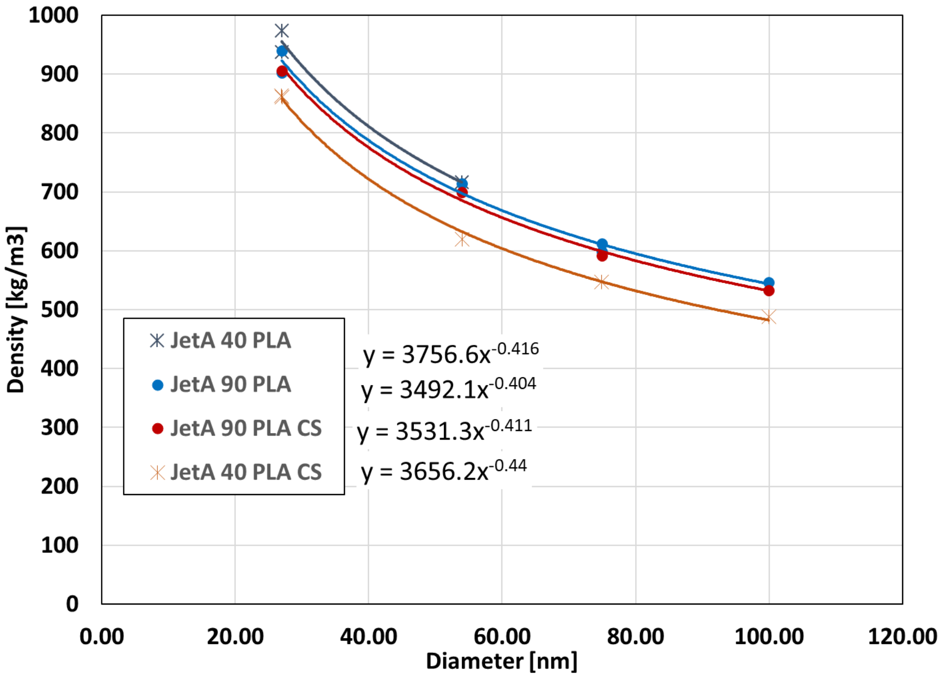
J-85 Jet-A fuel, variable thrust without CS, total density



J-85 jet-A fuel, variable thrust with CS, solid density



J-85 turbojet – influence of catalytic stripper (CS)

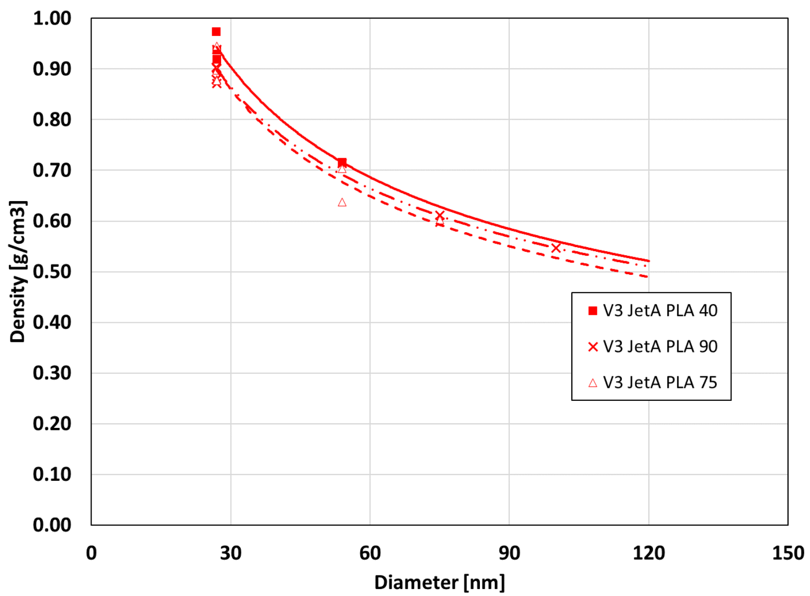


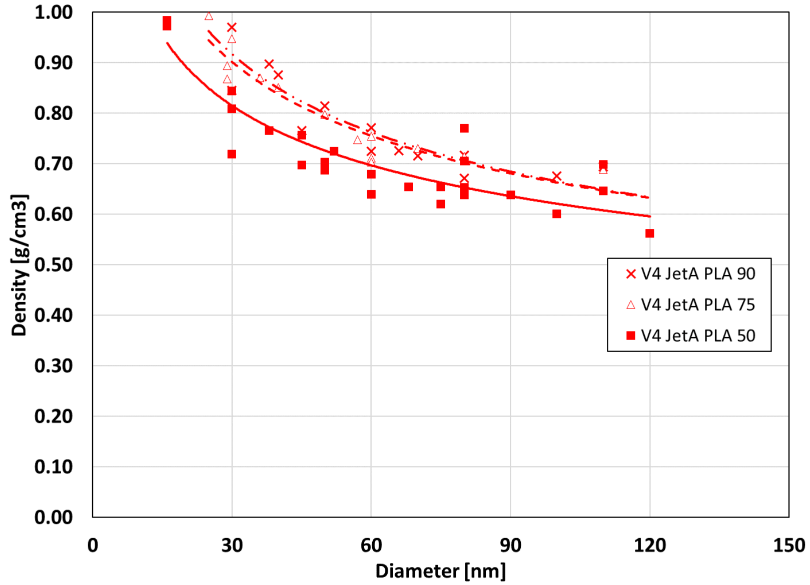
- At high load nearly the same density with / without CS
- At low load density reduced by CS
- Likely due to removal of semi-volatile materials

VARIAnT 4 measurements

- Used both DMA-CPMA-CPC and CPMA-DMA-CPC methods
- CPMA-DNA-CPC method allows faster scanning
- Selected results below

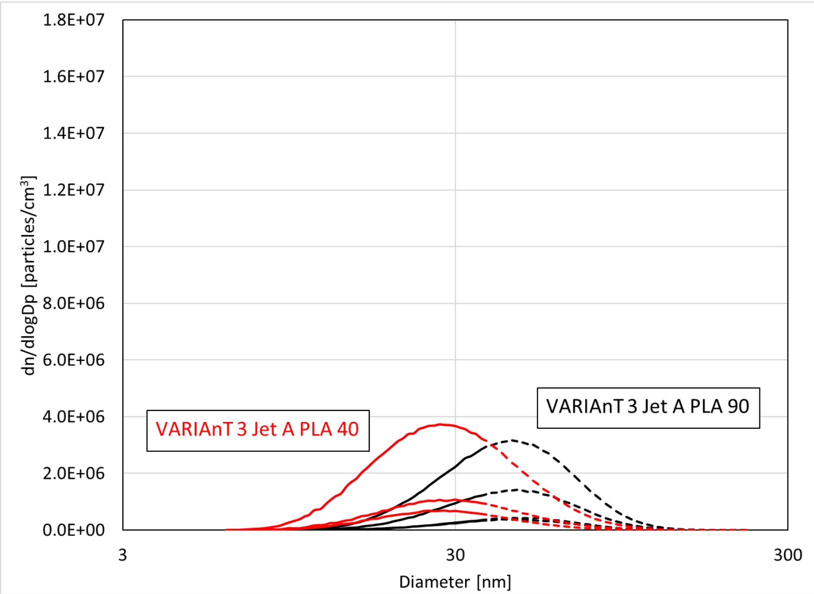
VARIAnT 3 and 4 density measurements
J-85, Jet A, DMA/CPMA, no CS

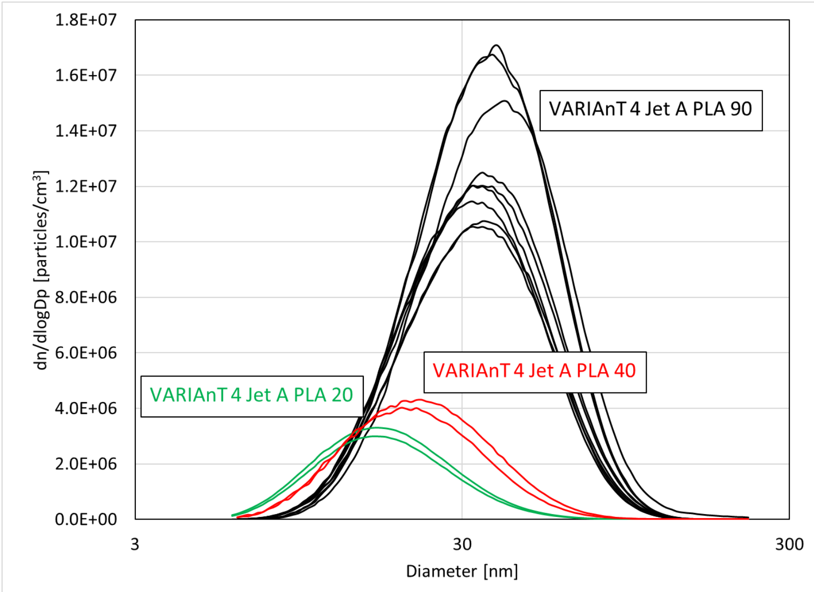




Approximately matched conditions – why the difference?

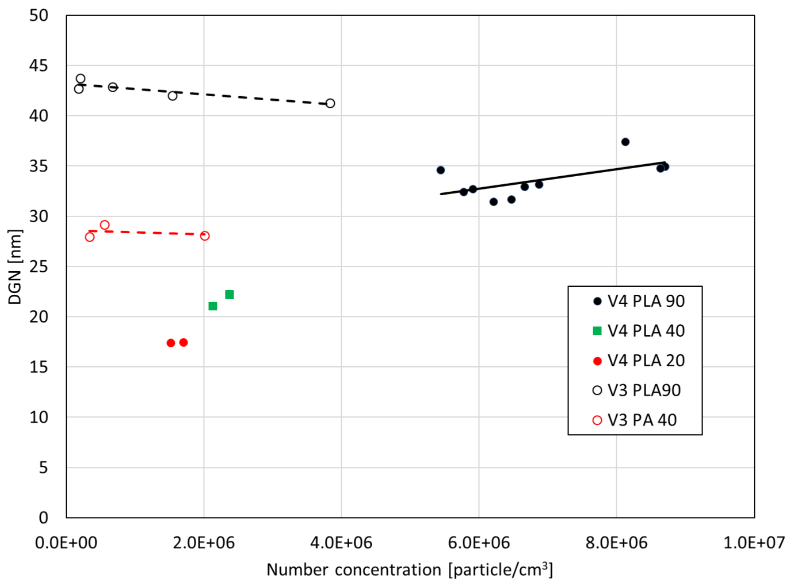
Comparison of VARIAnT 3 and 4 size distributions
Much higher V4 concentrations at PLA 90
Due mainly to less dilution.

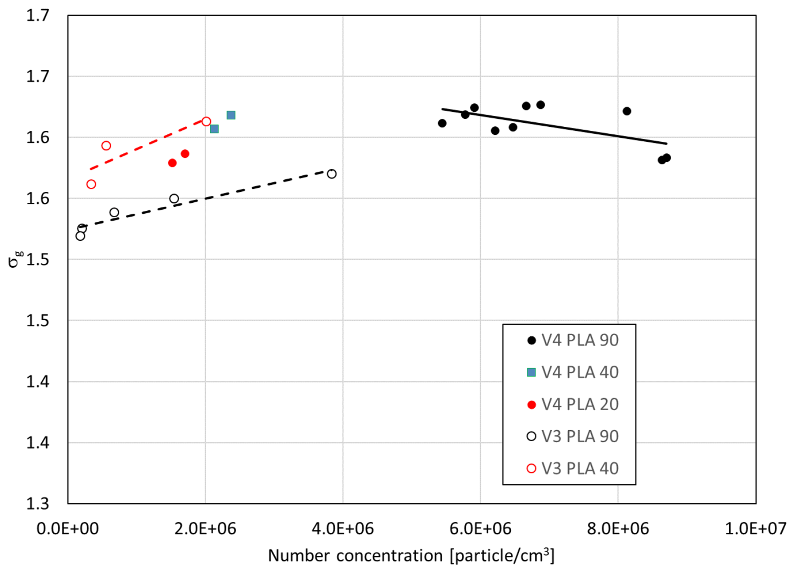




There does not seem to be anything remarkably different between V3 and V4 particle size distributions except that V4 particles are smaller and were measured over a wider concentration range

Comparison of VARIAnT 3 and 4 size distribution properties, DGN and sigma g





There does not seem to be anything remarkably different between V3 and V4 particle size distributions except that V4 particles are smaller and were measured over a wider concentration range

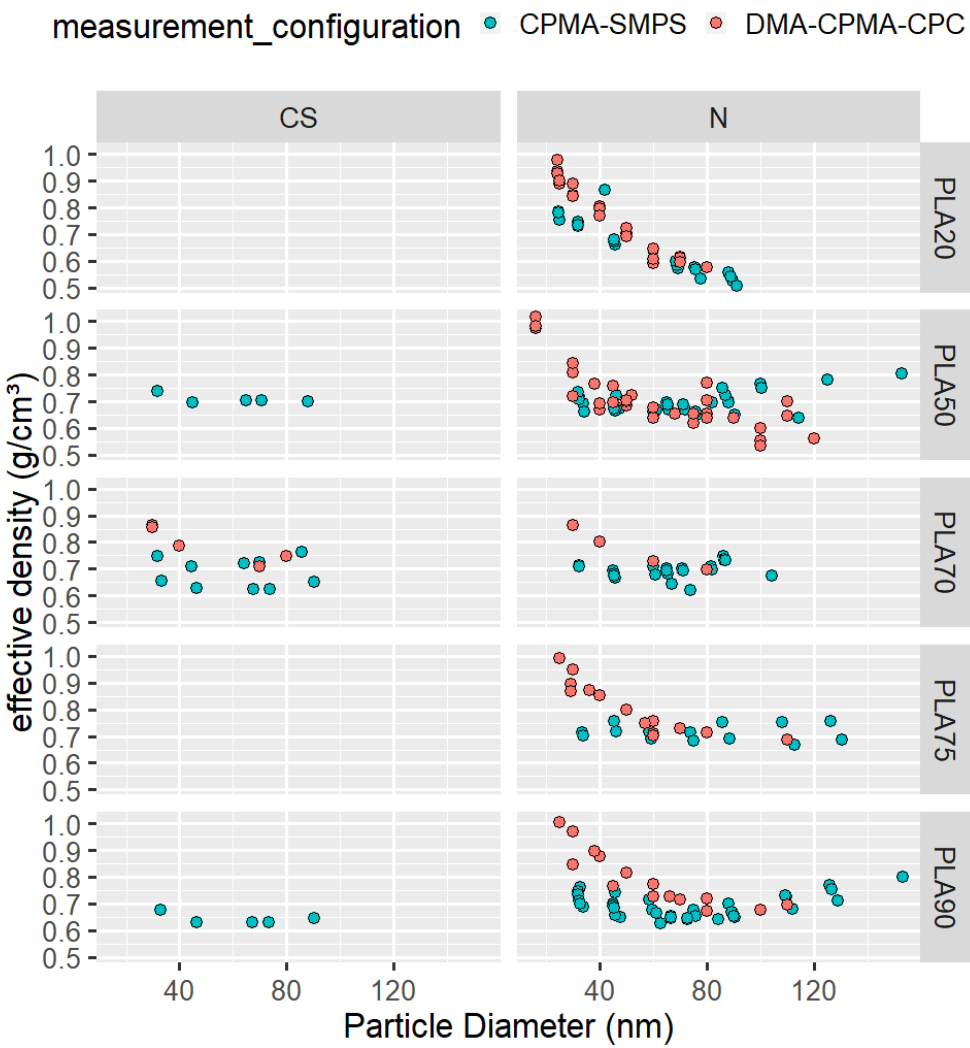
Comparison of DMA/CPMA and CPMA/DMA density measurements, VARIAnT 4

- Many cases show large difference in density distributions measured by the 2 methods
- Soot particles have very complex structures so that the 2 methods may be looking at different particles
- Nevertheless the results below are puzzling and need further study

Effective density Comparison between 2 test configurations

For J-85, Jet-A with and without catalytic stripper (showing only select PLAs)

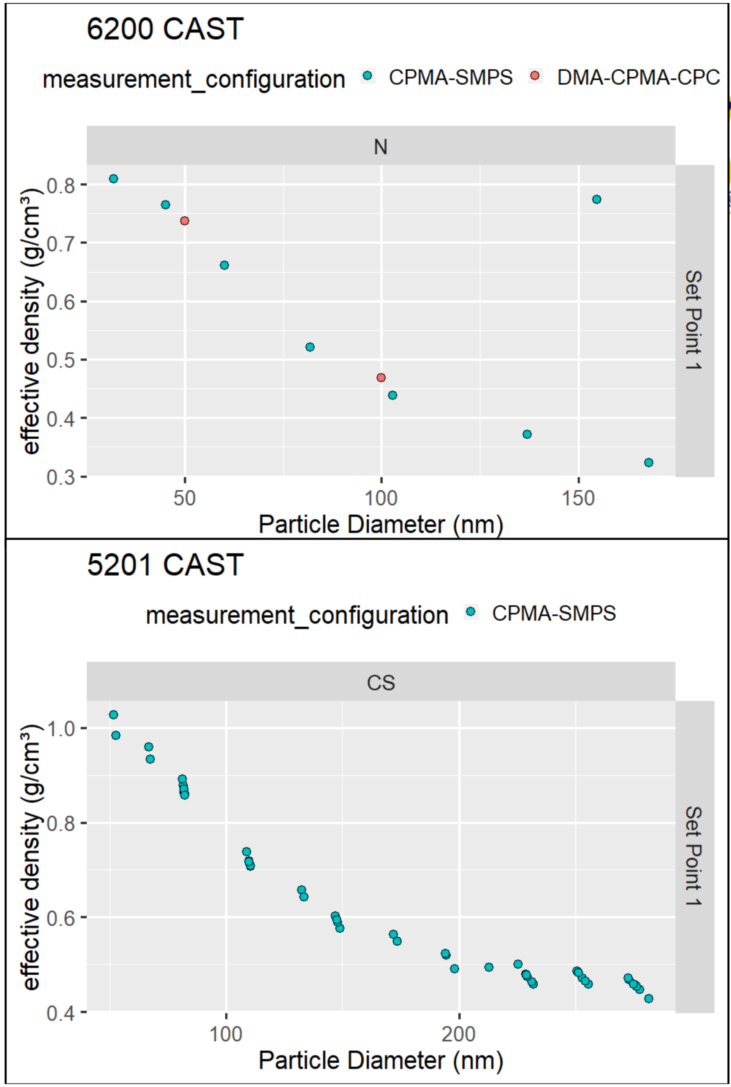
- CPMA-DMA-CPC method gives flatter density distributions, suggesting compact particles
- Effective density results between 2 different measurement configurations diverge at smaller particle diameters
- The effective density divergence between 2 configurations is more prominent at higher PLAs



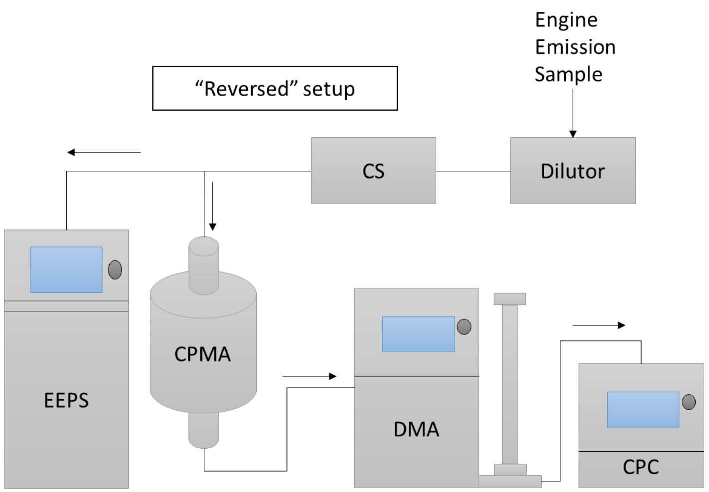
Effective Density Comparison between 2 measurement configurations: miniCASTs

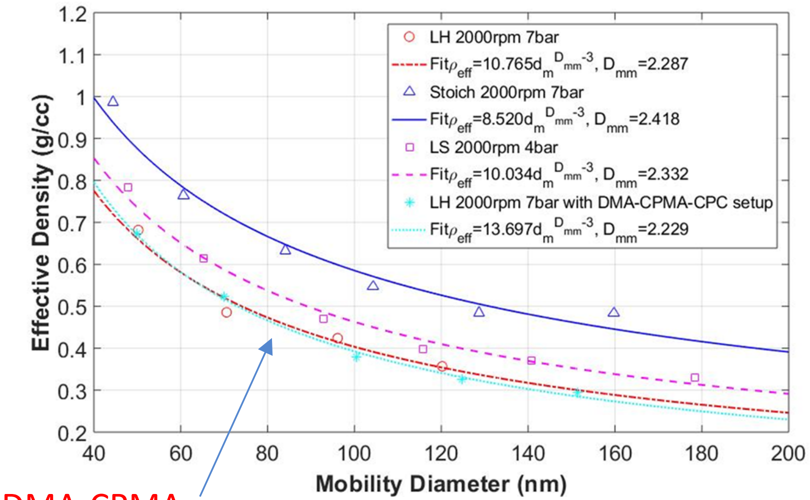
with (CS) and without (N) catalytic stripper

- Limited data between 2 methods, but both configurations give same result
- CPMA-SMPS method shows strong size dependence--not flat like some J-85 measurements



For piston engine testing in Minnesota we usually use the CPMA first configuration
Don’t see flat distributions
Limited tests of both configuration give identical results





Red is DMA-CPMA

Turquoise is CPMA-DMA

Summary

- Comparison of V3 and V4 density distributions shows significant differences
  - Similar engine and fuel conditions
  - Size distributions don't suggest reasons for the differences
- In VARIAnT 4 density measured using 2 different configurations (1) DMA-CPMA-CPC (commonly used) and (2) CPMA-DMA-CPC
  - Method 1 gives decreasing density with size ~$Dp^{-0.3}$ – $Dp^{-0.6}$ equivalent to mass-mobility coefficients of ~ 2.4 - 2.7
  - Method 2 gives density nearly independent of size for many test conditions, especially J-85 at high load, equivalent to mass-mobility coefficients of ~ 3
  - However, with the propane flame, both methods give essentially the same decreasing density with size.
  - Piston engine tests at U of M show essentially the same decreasing density with size, for both configurations.
  - This needs further study

Acknowledgement

- This work is part of a large series of studies "Variable Response In Aircraft non-volatile PM (nvPM) Testing (VARIAnT) 1 through 4 with many participants

- Today's presentation is based on "Variable Response In Aircraft nvPM Testing (VARIAnT): VARIAnT 3 and 4 Updates - Particle Properties: log normality and density," presented at SAE International E-31P Committee, Saclay, France, June 2019

- We thank the USEPA for their generous support

Thank you – questions?

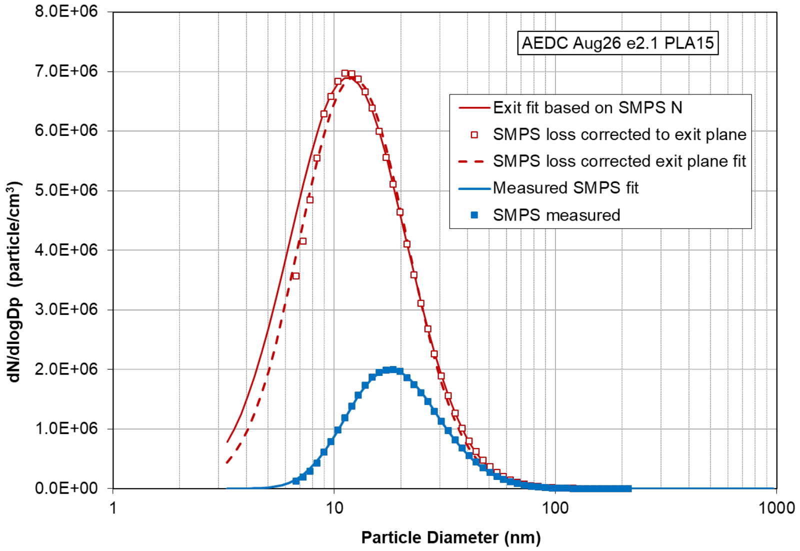
Some VARIAnT Study Goals

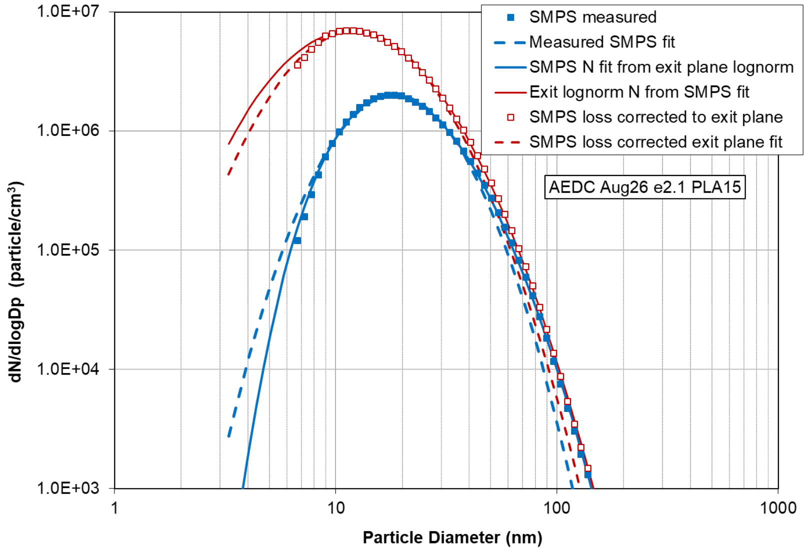
- Improving measurement of solid particle mass and number from aircraft engines
- Evaluation of the PM mass instruments with respect to:
  - Sensitivity over a range of particle morphologies and size, especially smaller particles
  - Sensitivity to BC concentrations at or near LOD
  - Compliance with the applicability requirement for engine certification
  - Calibration source and sampling system
- Evaluating and improving line loss estimation method being developed for SAE including:
  - Investigation of log normality of engine exhaust particle size distributions
  - Investigation of the measurement of density vs. particle size

Testing lognormal assumption

- We assume the distribution is lognormal at the exit plane, not at the measurement plane
- Must know line penetration to correct data to exit plane
- Tests for lognormal
  - Visual shape
  - Shape must be the same for all moments, number, surface, volume
  - Compare geometric standard deviations, sigma g
- Finding sigma g
  - Direct calculation, truncation error
  - Fits, find exit plane distribution that
    - Minimizes error at exit plane (loss correction errors amplified at small sizes)
    - Minimizes error at measurement plane (less error, most stable)

Example of *good* fit to lognormal distribution VARIAnT 2 Jet A PLA15





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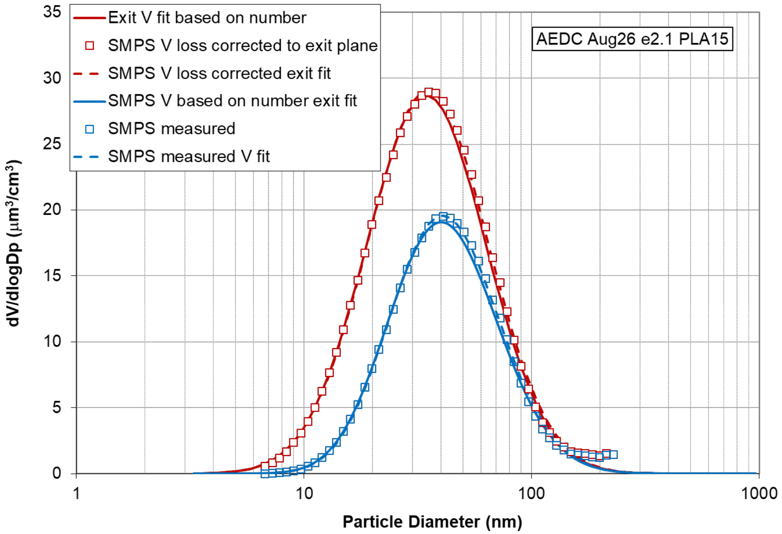
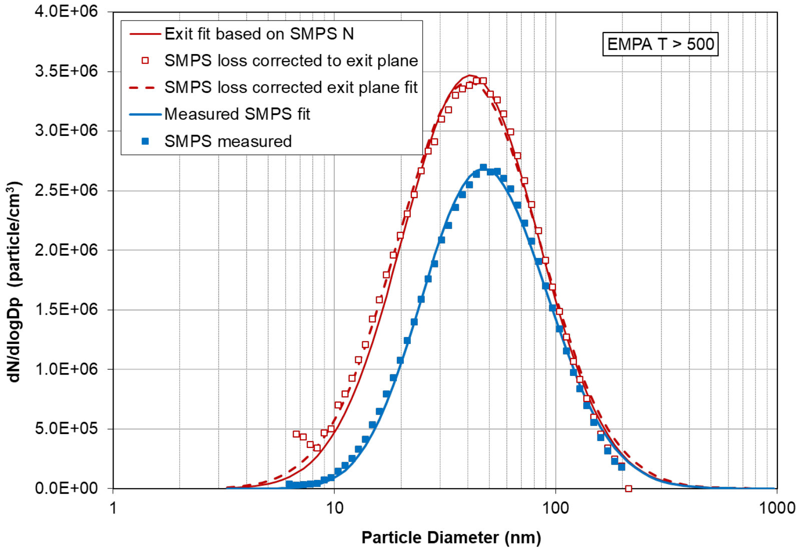
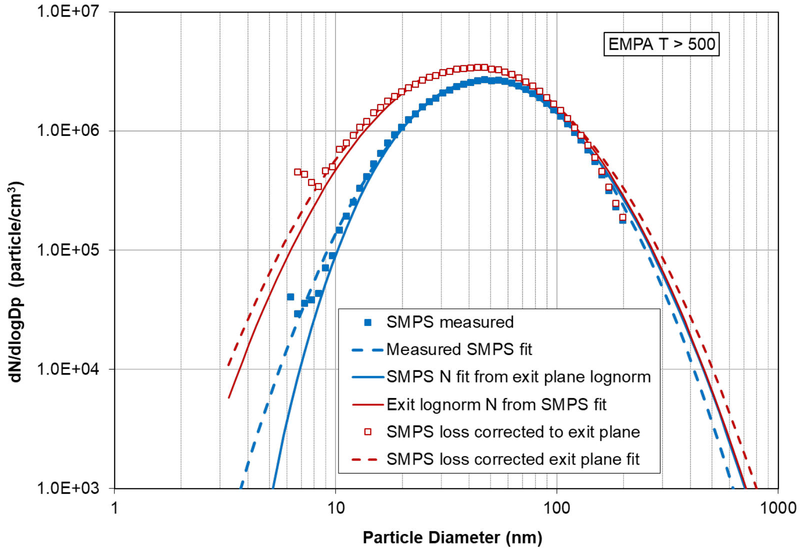


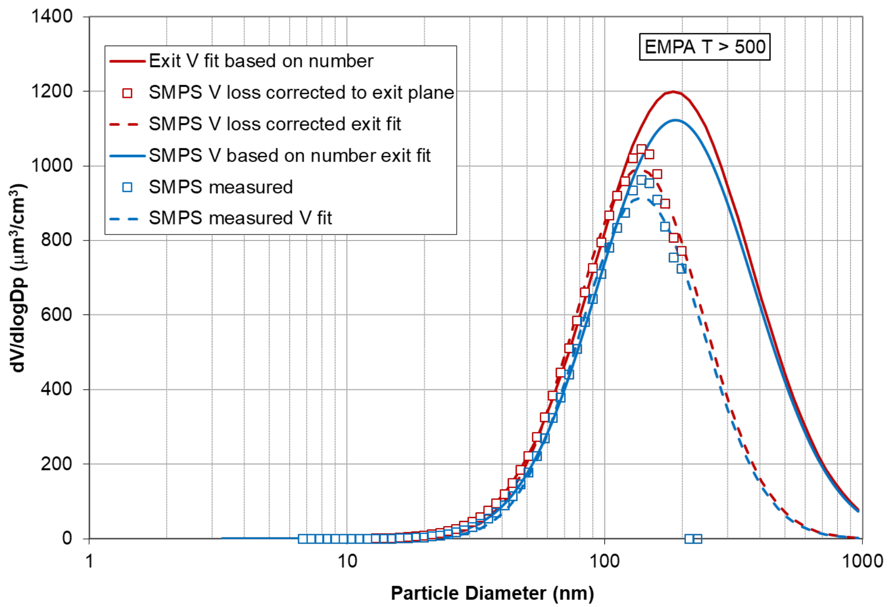
AEDC Aug26 e2.1 PLA15								
Condition	Fit or Calculated	Fit or calculation plane	Parameter plane	DGN	sigma N	DGV	Sigma V	Difference
Measured	calculated	SMPS	SMPS	19.2	1.59	43.7	1.76	-9.34%
Measured	fit N	SMPS	SMPS	18.4	1.61	36.3	1.61	0.00%
Measured corrected to exit	calculated	Exit	Exit	14.1	1.60	36.1	1.84	-13.33%
Measured corrected to exit	fit N	Exit	Exit	12.2	1.75	31.0	1.75	-4.95%
Measured corrected to exit	fit V	Exit	Exit	11.6	1.83	35.0	1.83	
Exit plane model	fit N	SMPS	Exit	11.6	1.83	34.4	1.83	0.43%
Exit plane model	fit V	SMPS	Exit	12.0	1.82	35.1	1.82	

Example of *poor* fit to lognormal distribution EMPA data, T_{exh} > 500



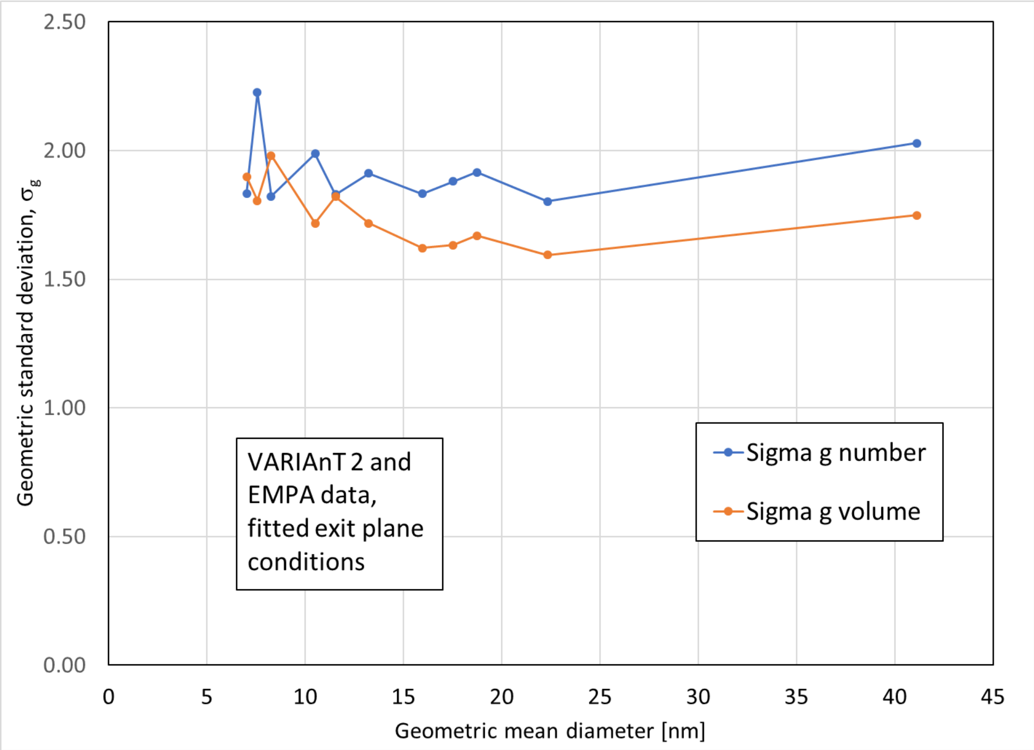


Example of ***poor*** fit to lognormal distribution EMPA data, $T_{exh} > 500$

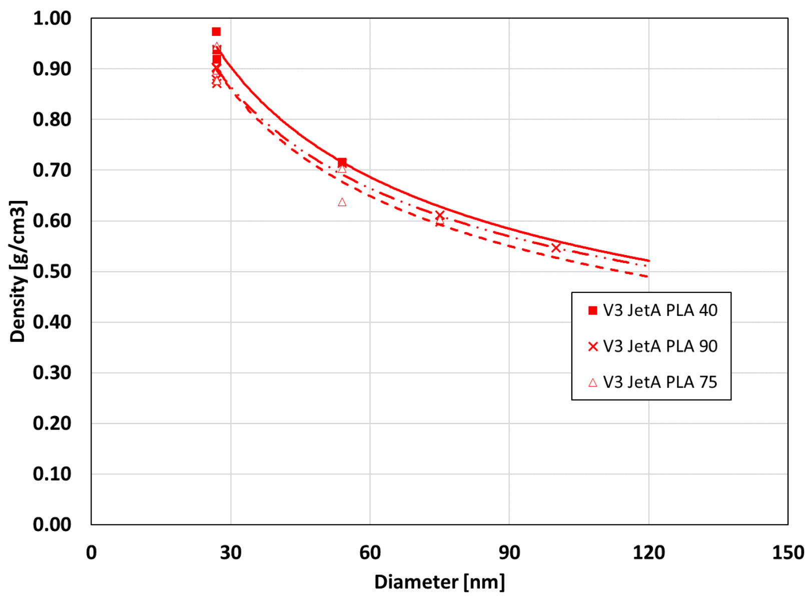


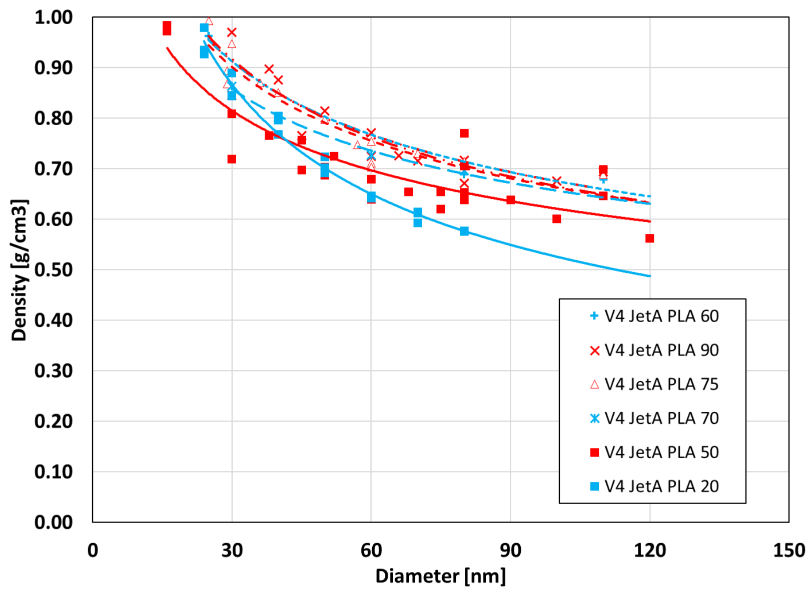
EMPA T > 500								
Condition	Fit or Calculated	Fit or calculation plane	Parameter plane	DGN	sigma N	DGV	Sigma V	Difference
Measured	calculated	SMPS	SMPS	47.0	1.84	109.7	1.53	20.70%
Measured corrected to exit	calculated	Exit	Exit	39.5	2.04	106.9	1.56	30.97%
Measured corrected to exit	fit N	Exit	Exit	40.3	2.10	208.5	2.10	16.02%
Measured corrected to exit	fit V	Exit	Exit	52.3	1.76	136.5	1.76	0.00%
Exit plane model	fit N	SMPS	Exit	41.1	2.03	184.5	2.03	13.79%
Exit plane model	fit V	SMPS	Exit	53.3	1.75	136.1	1.75	0

Difference between number and volume weighted sigma g is measure of departure from lognormal



VARIAnT 3 and 4 density measurements J-85, Jet A, DMA/CPMA, no CS

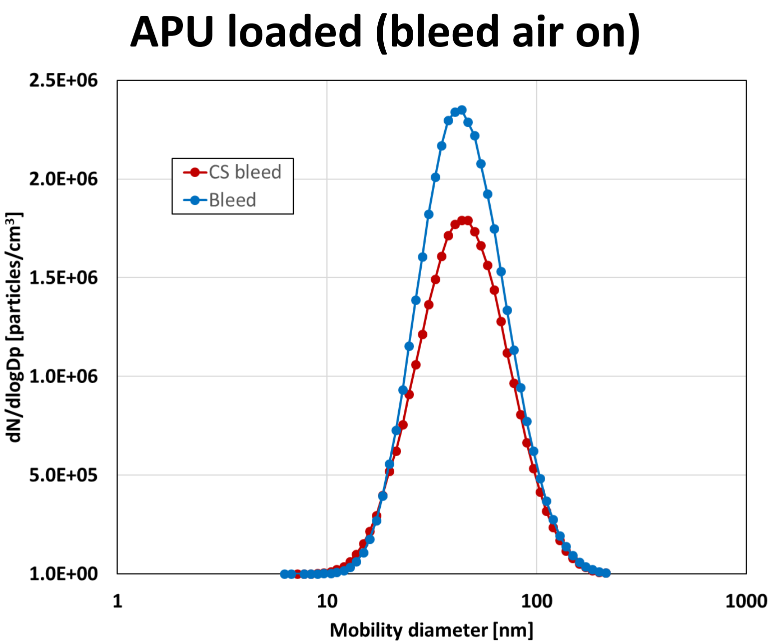


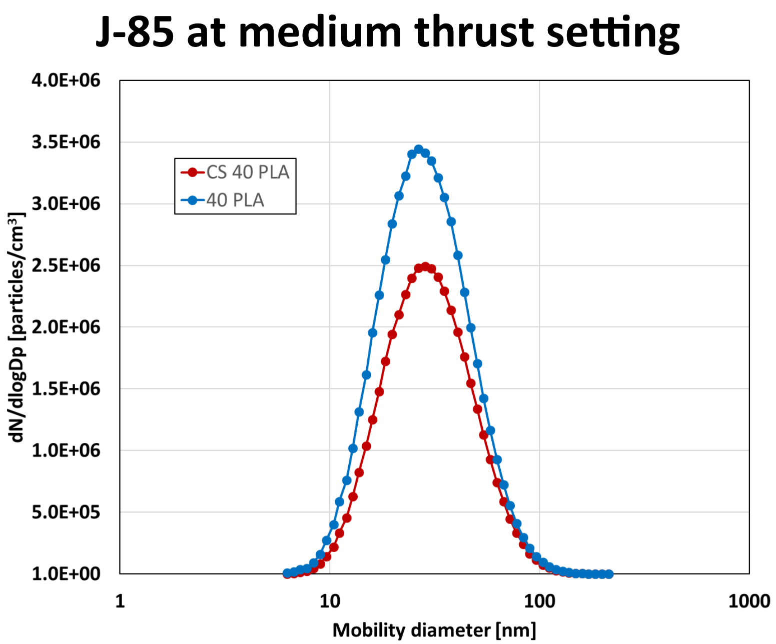


Density measurements

- Density needed for current line loss method
- Knowledge of size dependent density might allow direct measurement of particle mass from a size distribution measurement using integrated particle size distribution method

Size distributions – gas turbine APU and J-85 with/without CS





CS has no influence on size measured by SMPS, density changes due to material in pores