A "2nd" (> 150 nm) Size Mode in Aircraft Gas Turbine Engine Exhaust

D. Kittelson[1], A. Zelenyuk[2]

[1]Department of Mechanical Engineering, University of Minnesota.

[2]U.S. Department of Energy, Pacific Northwest National Laboratory

28th ETH Nanoparticles Conference 2025

16-19 June 2025

ETH Zurich

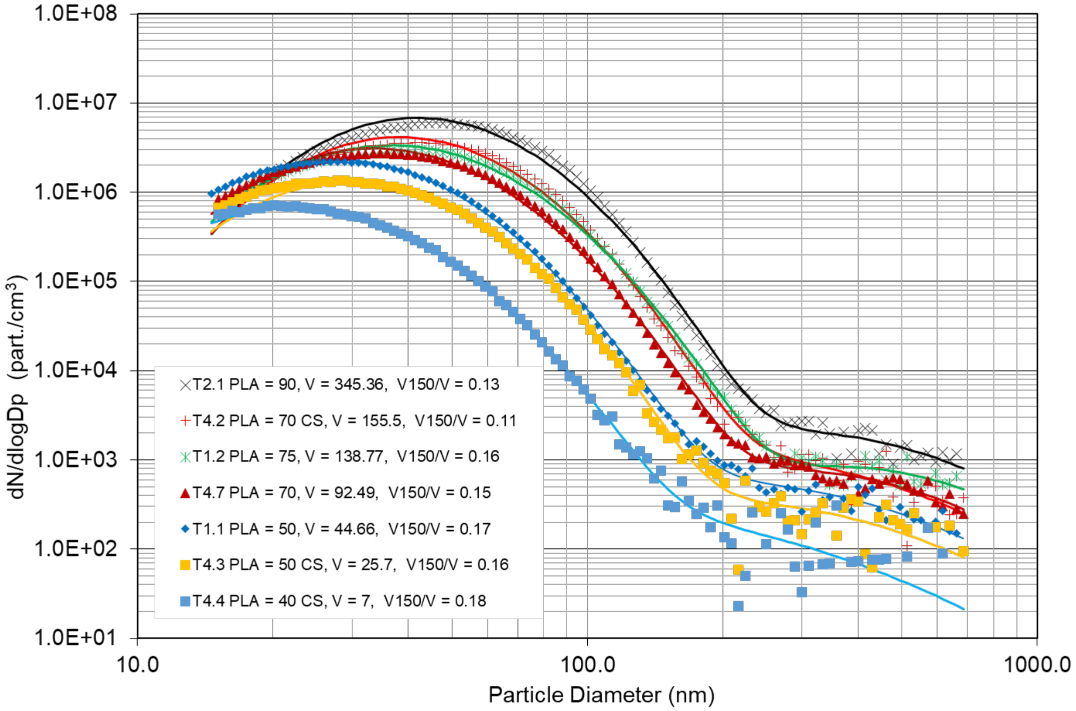
Non-volatile particles for aircraft gas turbines: a Secondary mode mainly above about 150 nm?

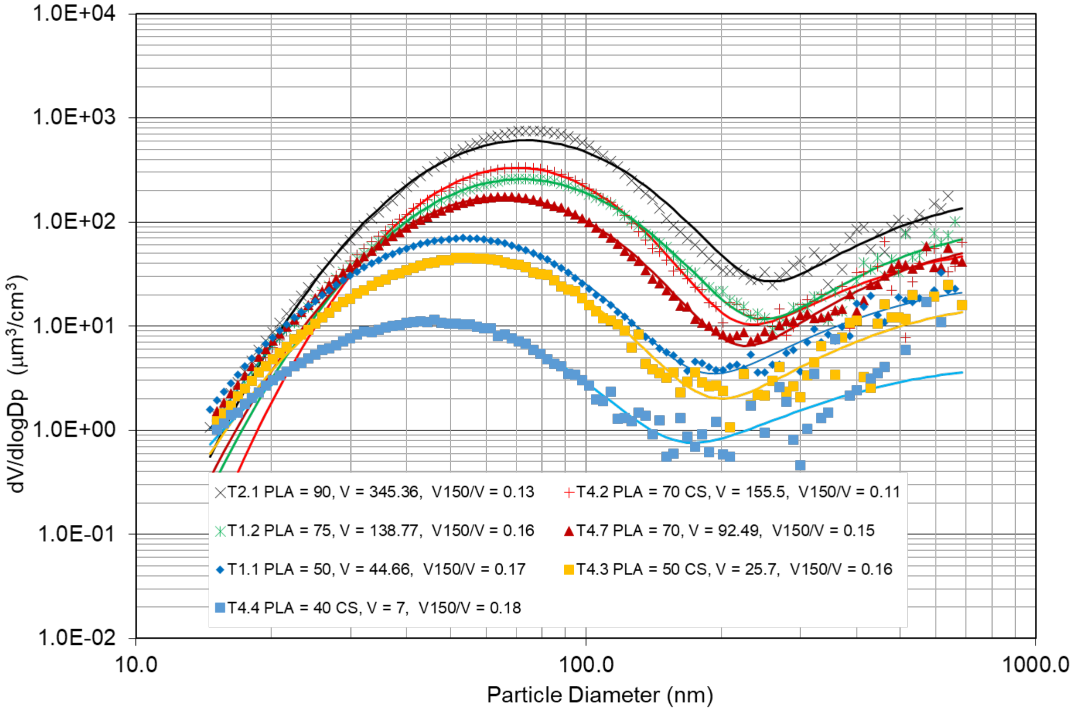
- A significant mass and volume of particles larger than ~ 150 nm were observed during a series of measurement campaigns, VARIAnT 1-4 (2014-2018), conducted by the U. S. Environmental Protection Agency in collaboration with the U. S. Air Force's Arnold Engineering Development Complex.
- The main purpose of these campaigns was to refine methodology for measurement of non-volatile particles from aircraft engines.
- The results presented here are mainly based on the last campaign, VARIAnT 4, but the secondary mode was observed in all 4 campaigns
- Two gas turbine engines and a variety of fuels and conditions were tested
  - General Electric J-85 turbojet
  - Gas turbine aircraft auxiliary power unit (start cart)
  - Fuels – Jet A, 30% and 70% blends of Camelina (SAF) in Jet A
  - Sampling system similar to the regulatory system

Instruments

Measured Parameter(s)	Instrument Make/Model	Campaign and Number of Analyzers V3	V4
Total particle mass	Multifilter Sampler w/25-mm Teflon and backup quartz filters	1	1
Black carbon mass concentration	AVL Model 483 Micro Soot Sensor (MSS); 0.001 – 300mg/m^3, detection limit ~0.005 mg/m^3	1	1
	AVL Model 483 Micro Soot Sensor Plus (MSSplus); 0.001 – 150 mg/m^3, detection limit ~0.001 mg/m^3	1 or 2[b]	1
	Artium Technologies LII-300 Laser Induced Incandescence Analyzer (LII-300)[d] ; 0.0002 – 20,000 mg/m^3	2	2-4[c]
	Aerodyne CAPS PM$_{SSA}$ [e] ; 0-500 µg/m^3, detection limit <0.5 µg/m^3 (3 σ, 1 second)	1	1
Organic and elemental carbon (OCEC)	Sunset Model 4 Semi-Continuous OCEC Analyzer	1	1
	Multifilter Sampler w/25-mm quartz filters + Sunset Laboratory Model 4L OCEC Analyzer	1	1
	Multifilter Sampler w/25-mm Teflon and backup quartz filters + Sunset Laboratory Model 4L OCEC Analyzer[f]	1	1
Total particle number concentration	AVL Particle Counter (APC) Aviation; 0 to 10,000 particles/cm^3; lower detection limit ~0.001 particles/cm^3		1
Particle size distribution	TSI Model 3936 Scanning Mobility Particle Sizer (Model 3081 differential mobility analyzer + Model 3776 condensation particle counter)	1	1
	TSI Model 3938 Scanning Mobility Particle Sizer (Model 3081 differential mobility analyzer + Model 3776 condensation particle counter)	1	3[g]
	TSI Model 3090 Engine Exhaust Particle Sizer (EEPS); mobility diameter range : 5.6-560 nm; 1 second average concentration lower limits : ~4200 particles/cm^3 at 5.6 nm and ~30 particles/cm^3 at 560 nm	1	1
	Cambustion Model DMS500 Fast Particle Analyzer mobility diameter range : 5 – 1000 nm; 1 second average concentration RMS noise : ~1500 particles/cm^3 at 5.6 nm and ~50 particles/cm^3 at 560 nm		1
Grids for analysis by transmission electron microscopy (TEM)	Naneos Partector; concentration range : 0-20,000 mm^2/cm^3; lower detection limit ~1 mm^2/cm^3	2	1
Particle characterization	Model 3081 differential mobility analyzer + Cambustion Centrifugal Particle Mass Analyzer (CPMA; mass range : 0.0002 – 1,050 fg) + Model 3025a condensation particle counter	1	1
	Cambustion Aerodynamic Aerosol Classifier (AAC)[i] ; aerodynamic diameter range : 25 – 5000 nm		1
	TSI Model 140 Quartz Crystal Microbalance/Micro-Orifice Uniform Deposit Impactor (QCM/MOUDI)[h]		1
Particle chemical composition	PNNL single particle mass spectrometer (miniSPLAT)		1

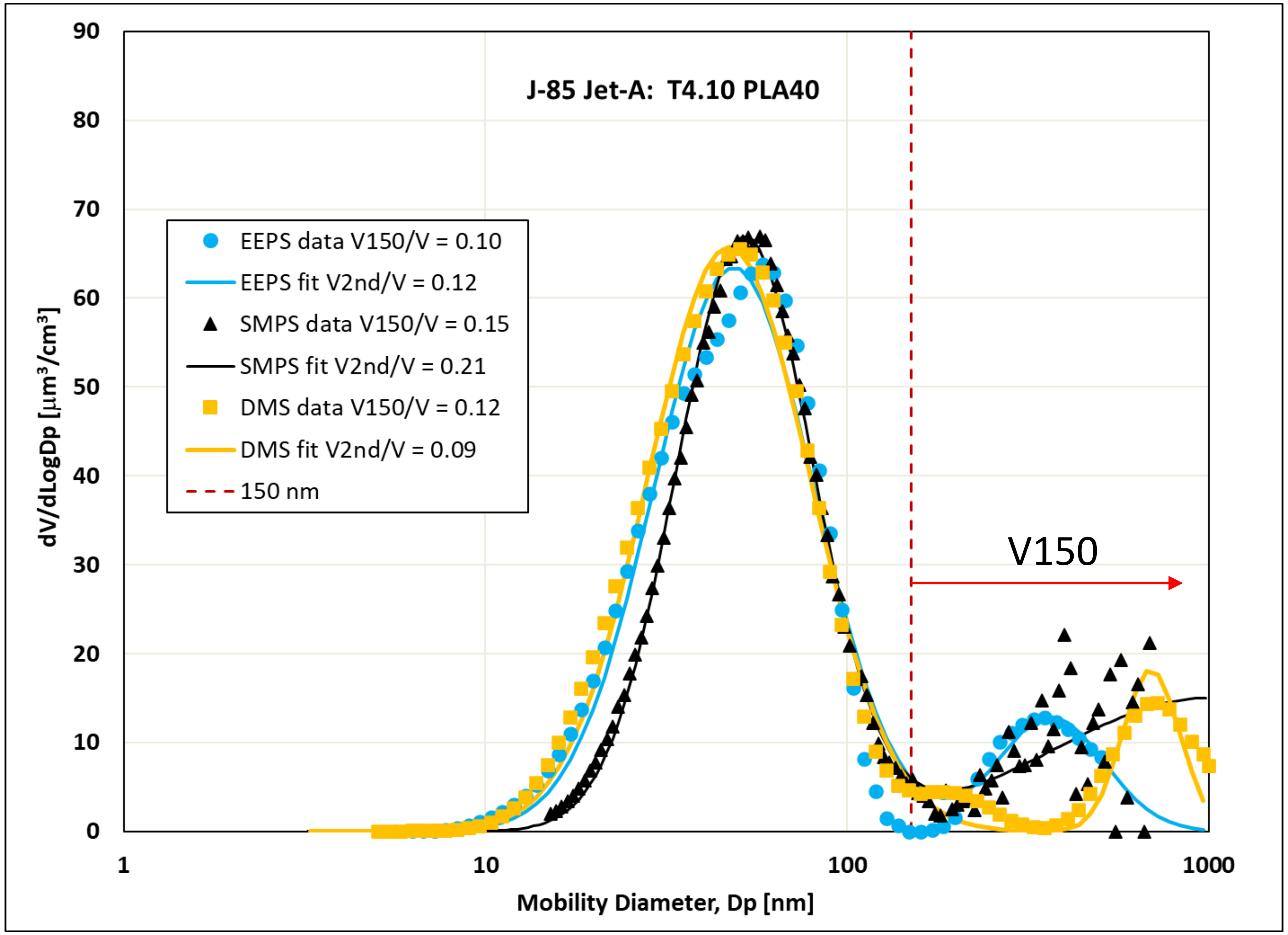
Typical SMPS number and volume distributions, size range 15 -690 nm, 2nd mode present in all



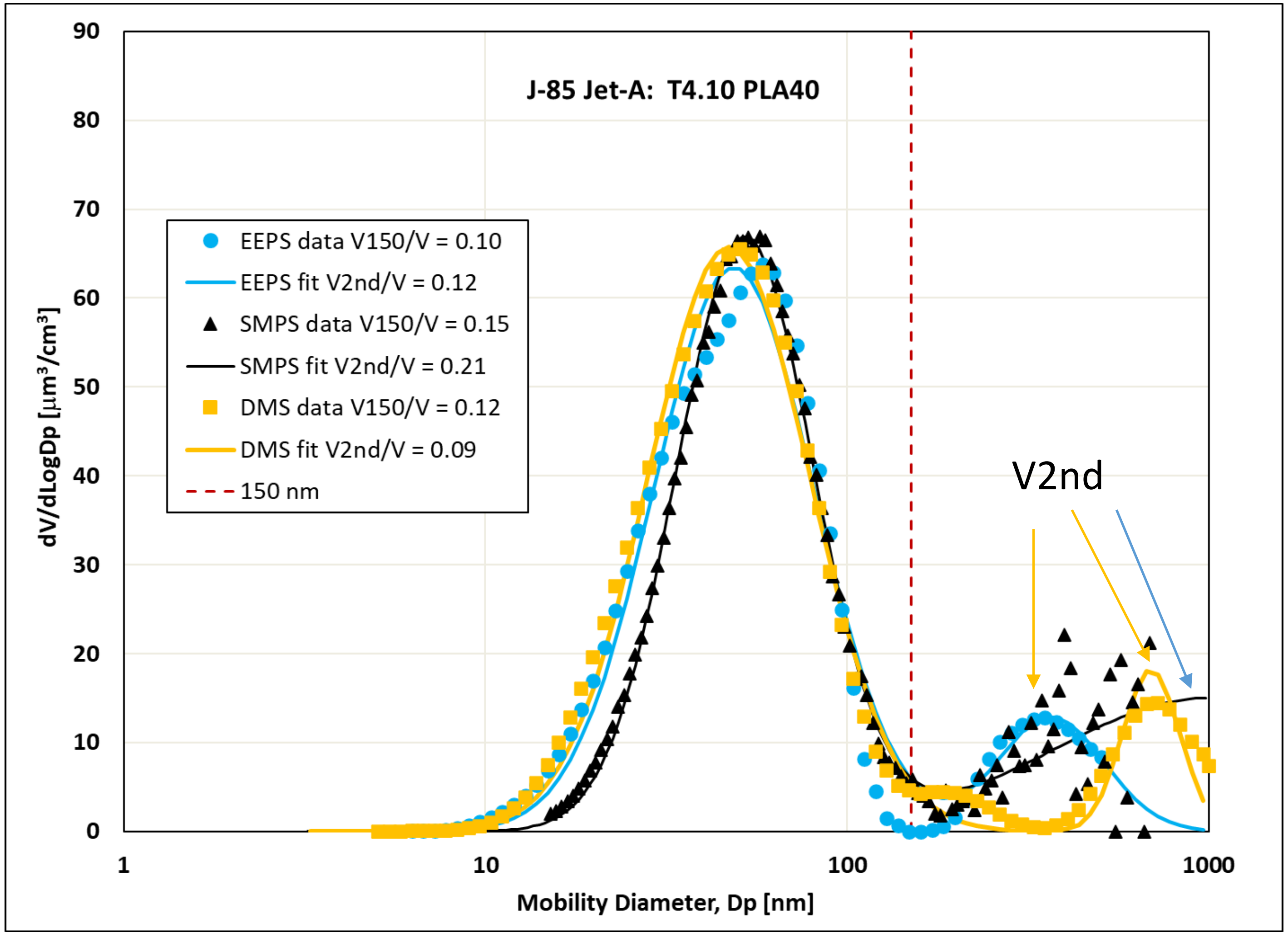


PLA is a measure of load or fuel flow, PLA15 idle, PLA90 maximum fuel flow, thrust

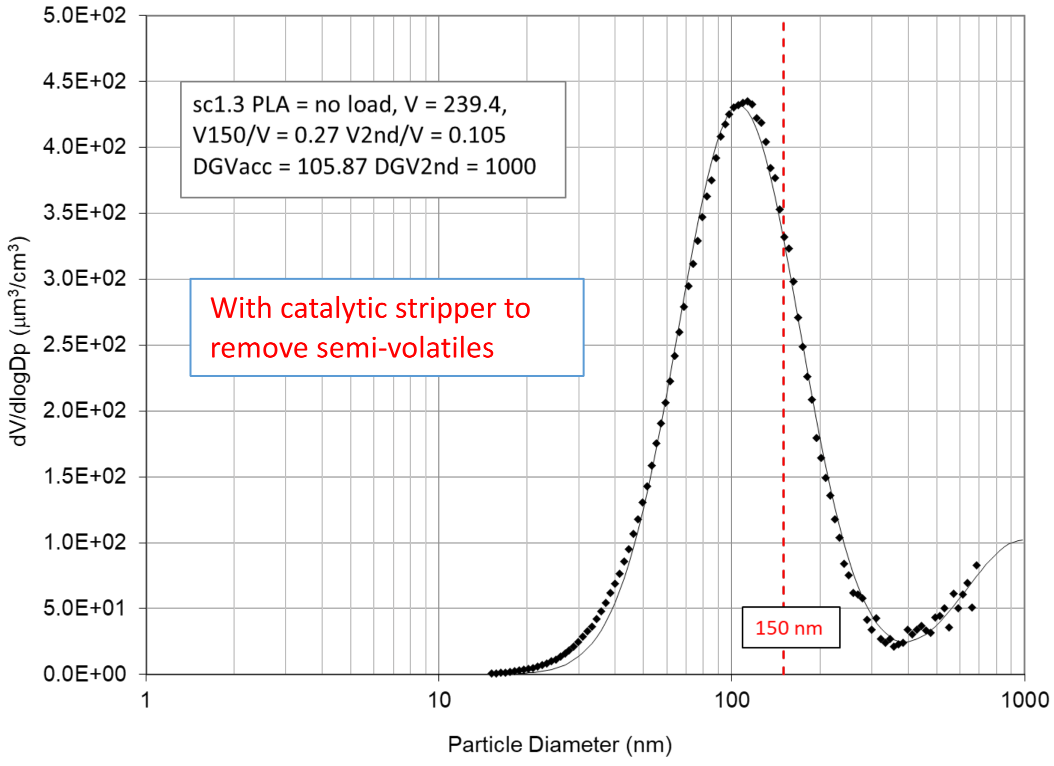
Comparing V150 and V2nd: EEPS (6-560 nm), SMPS (15-690 nm), DMS (5-1000 nm)

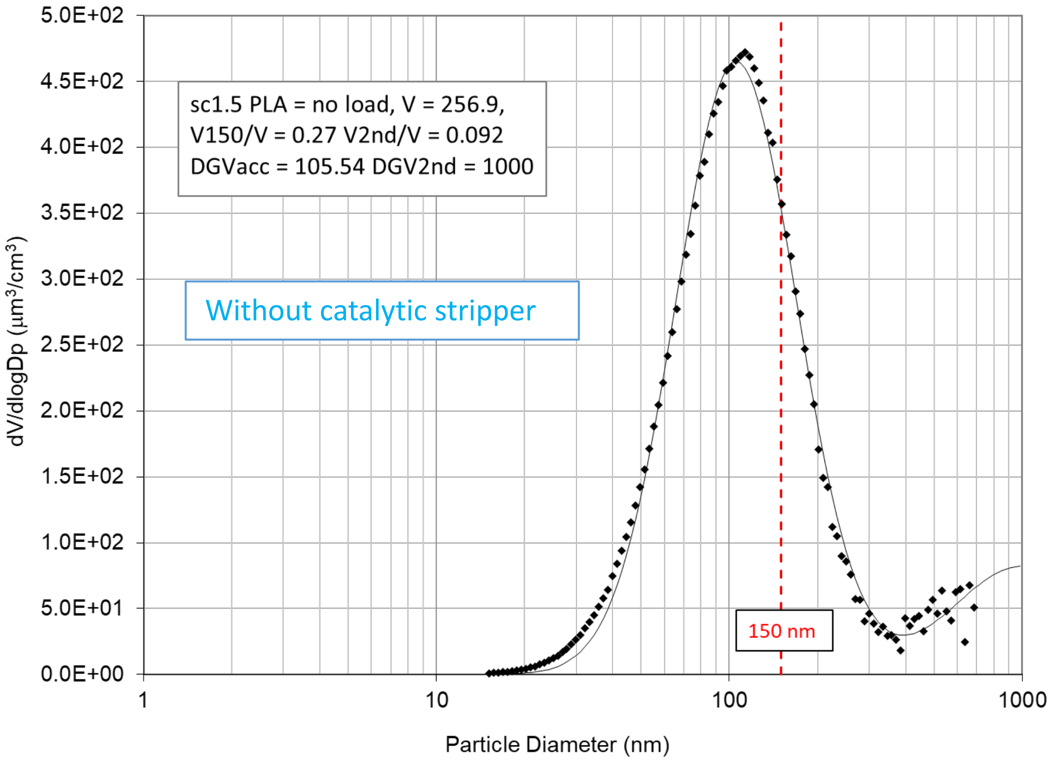


Comparing V150 and V2nd (fit): EEPS (6-560 nm), SMPS (15-690 nm), DMS (5-1000 nm)

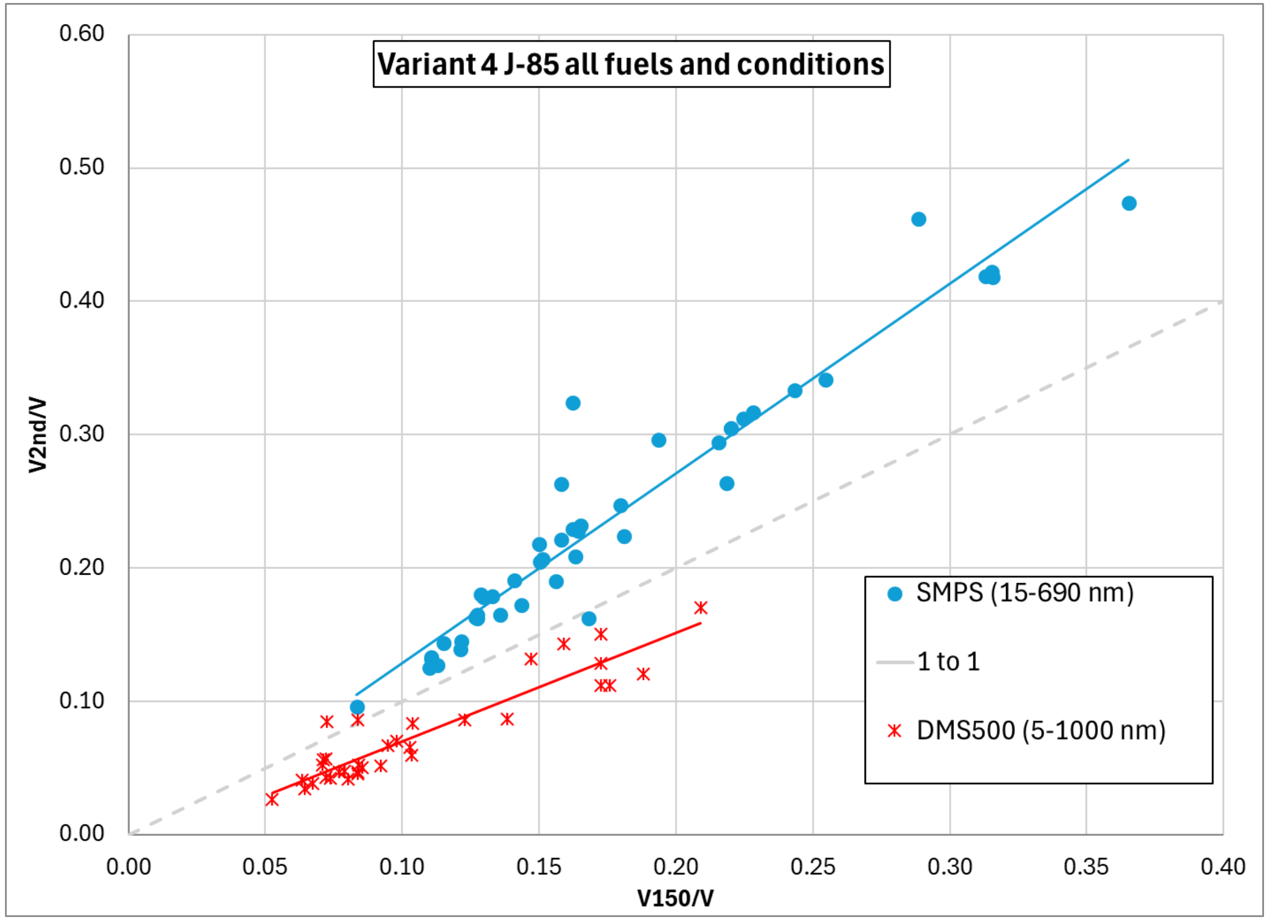


Start Cart (turbine APU) significant volume above 150 nm but small 2nd mode (fit)

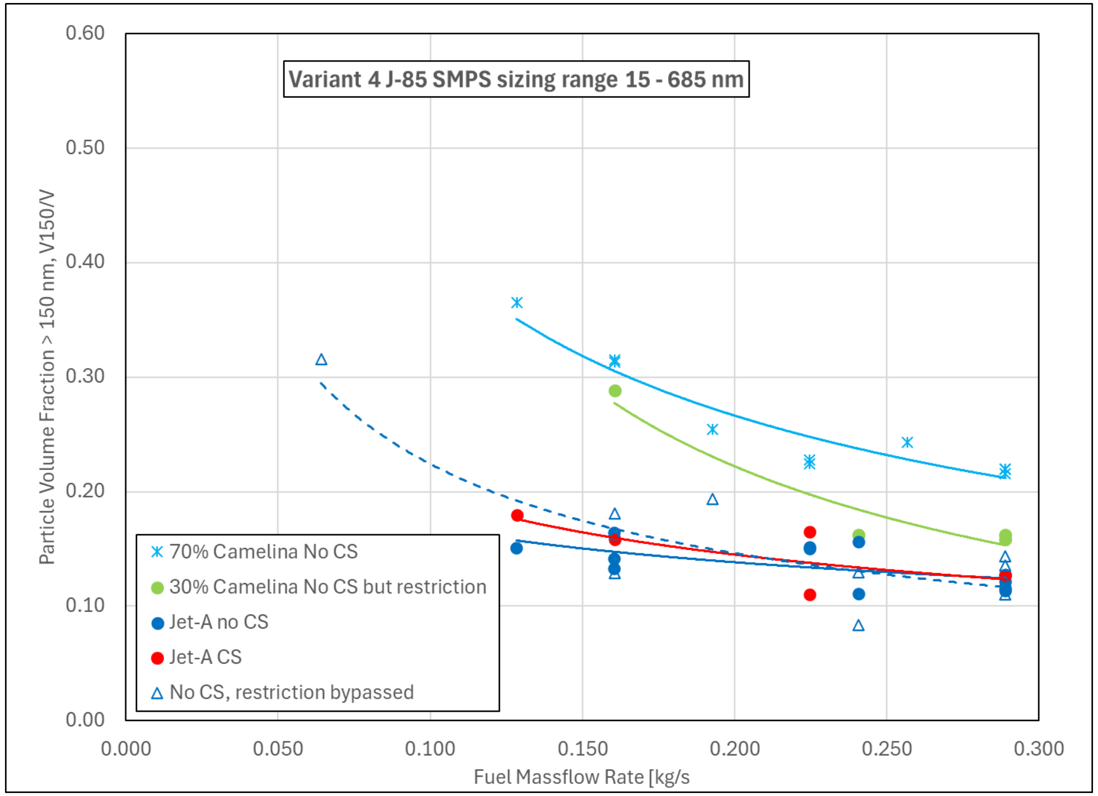


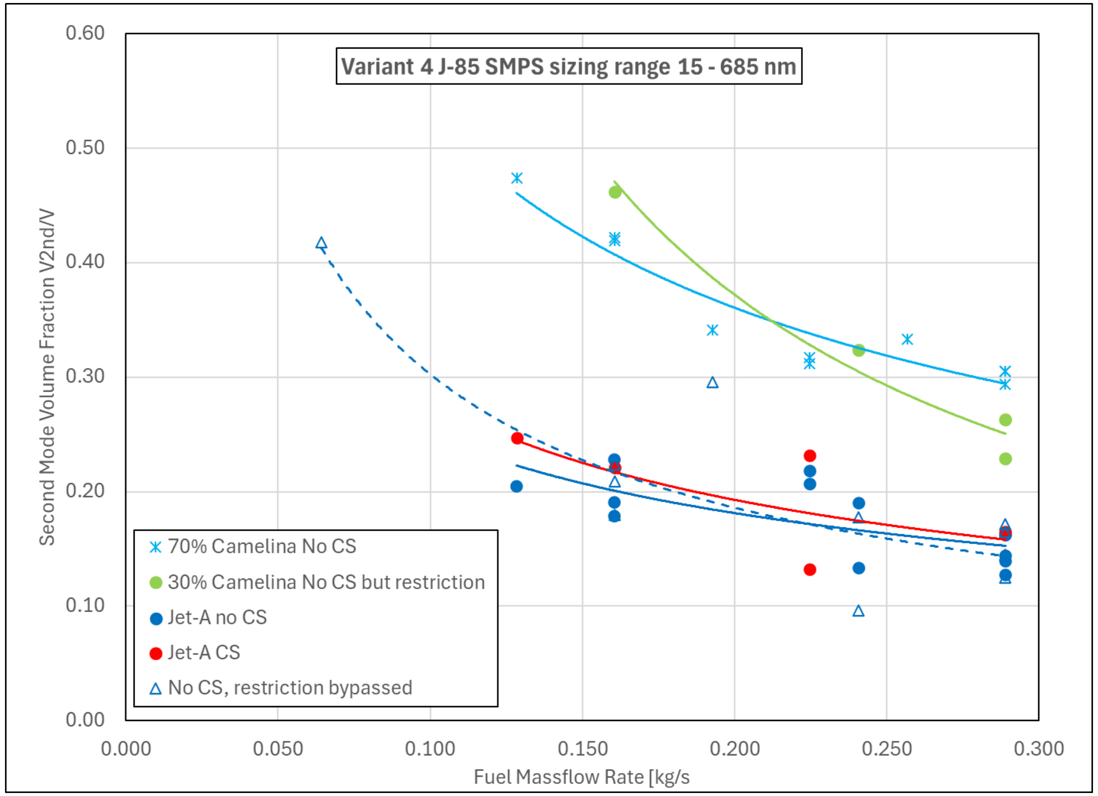


Comparison between SMPS and DMS, SMPS measures more V150/V and V2nd/V

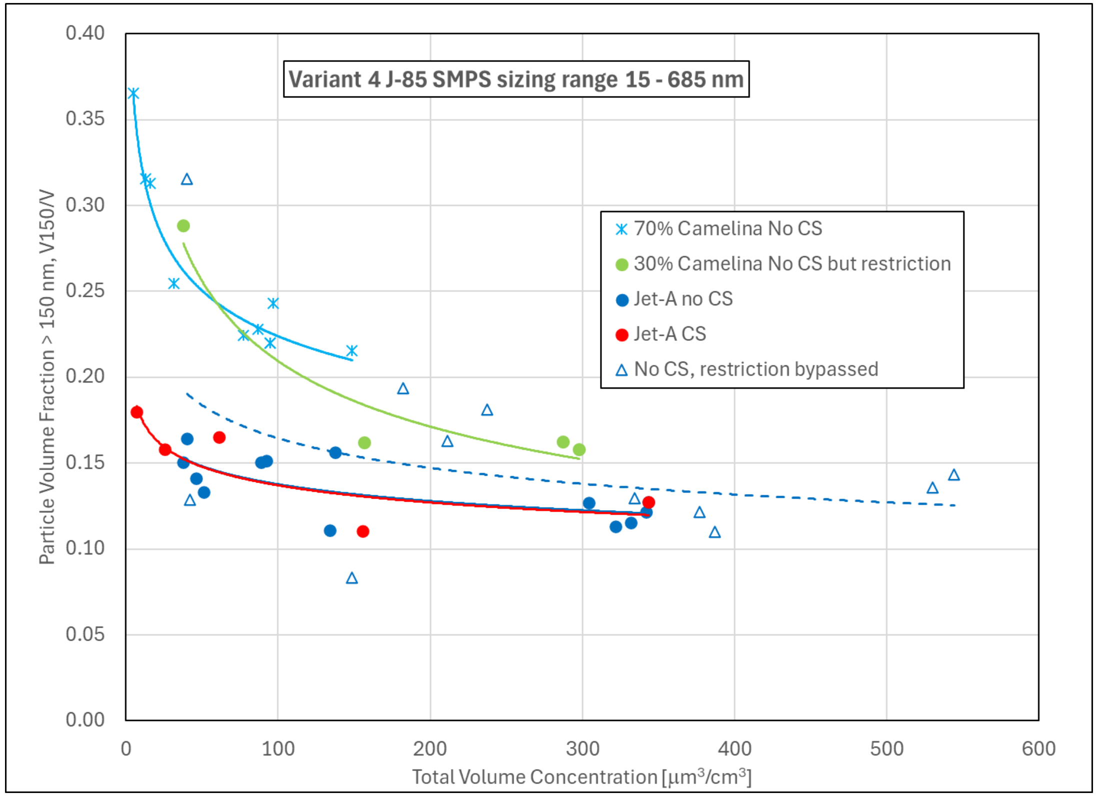


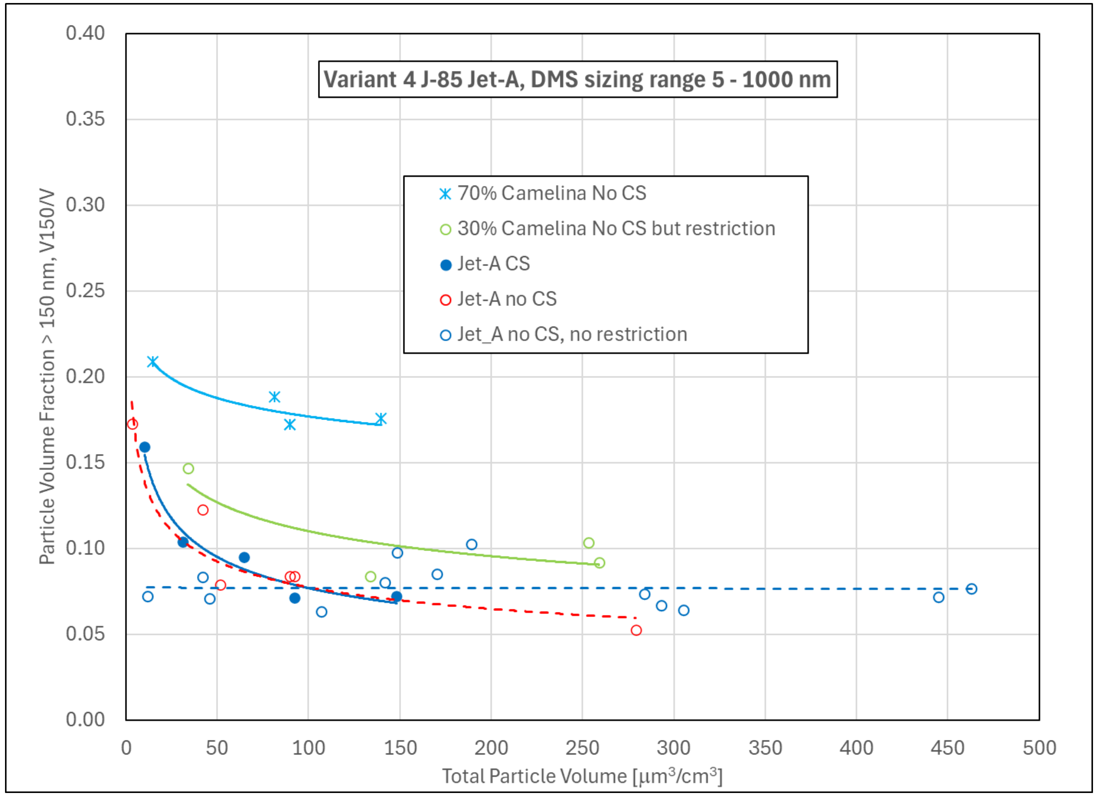
J-85 all fuels, V150/V and V2nd /V show similar trends with load, but V2nd /V is larger



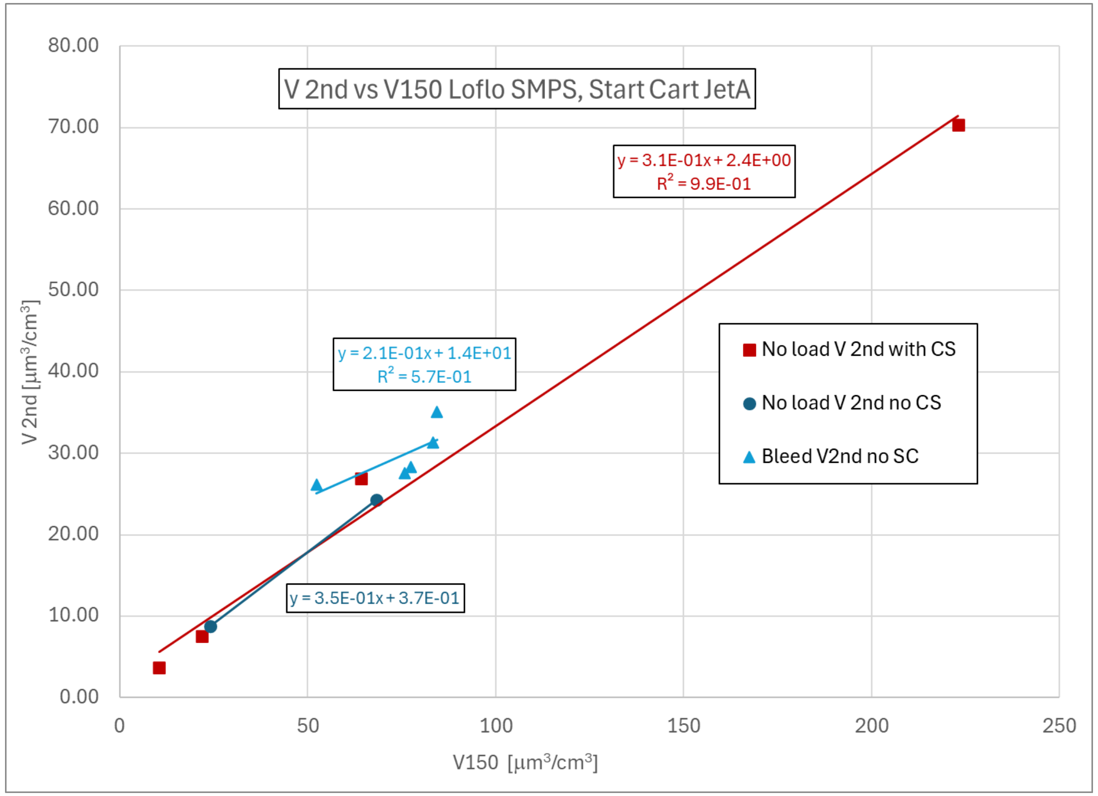


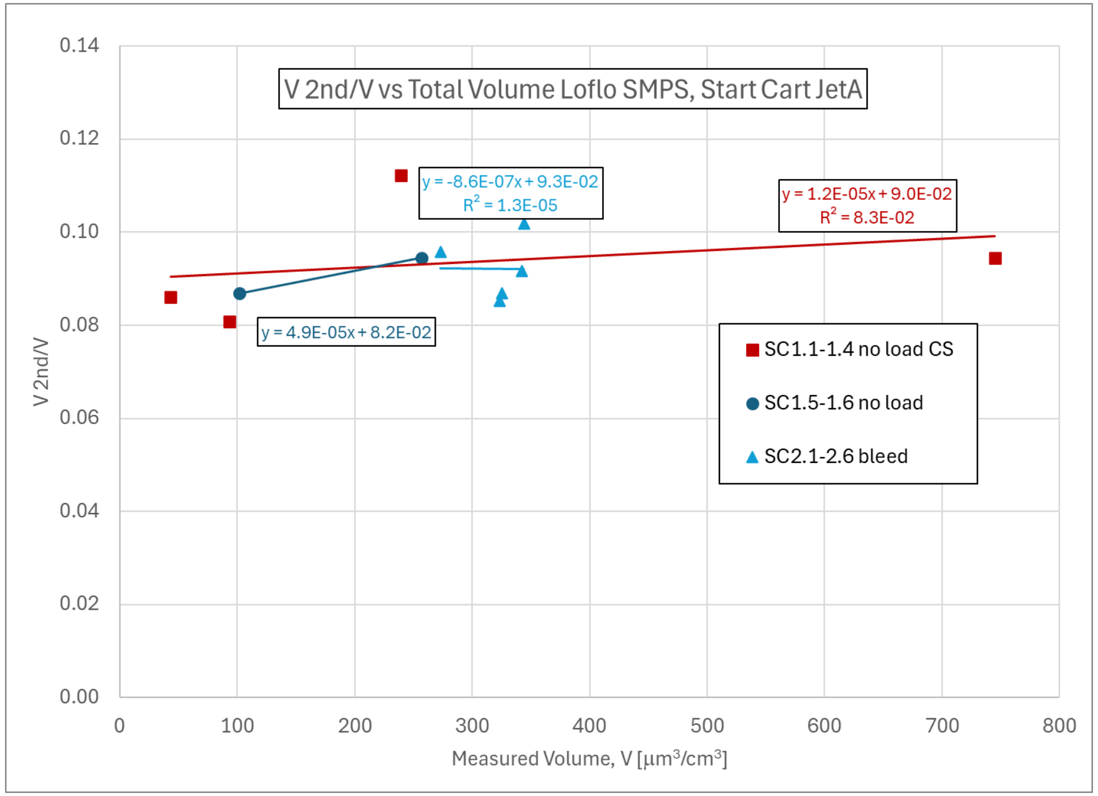
V150/V vs. total volume, SMPS and DMS show similar trends, but DMS measures smaller V150/V





Start Cart, ratio V2nd/V150 smaller than J-85 and trend with concentration is very different

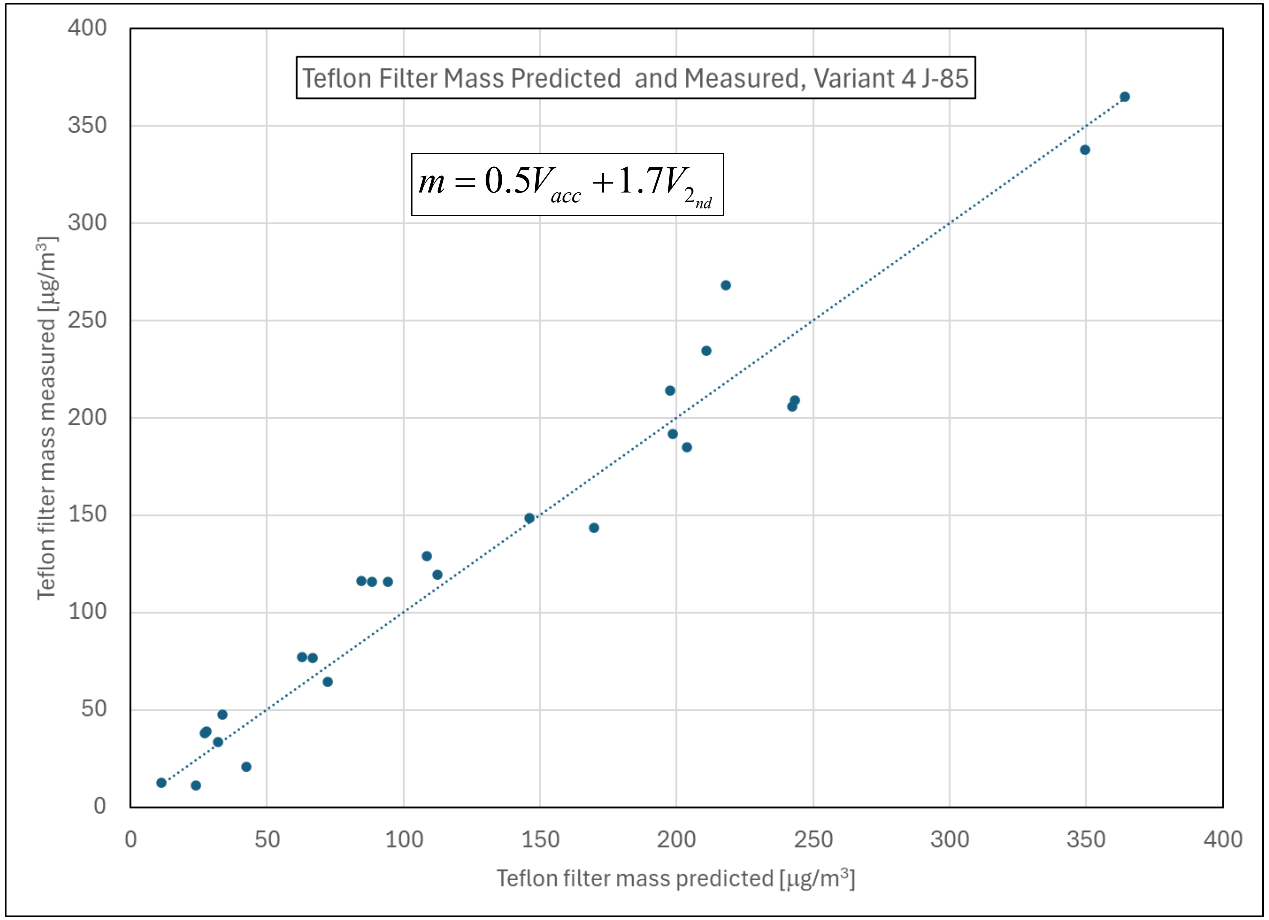




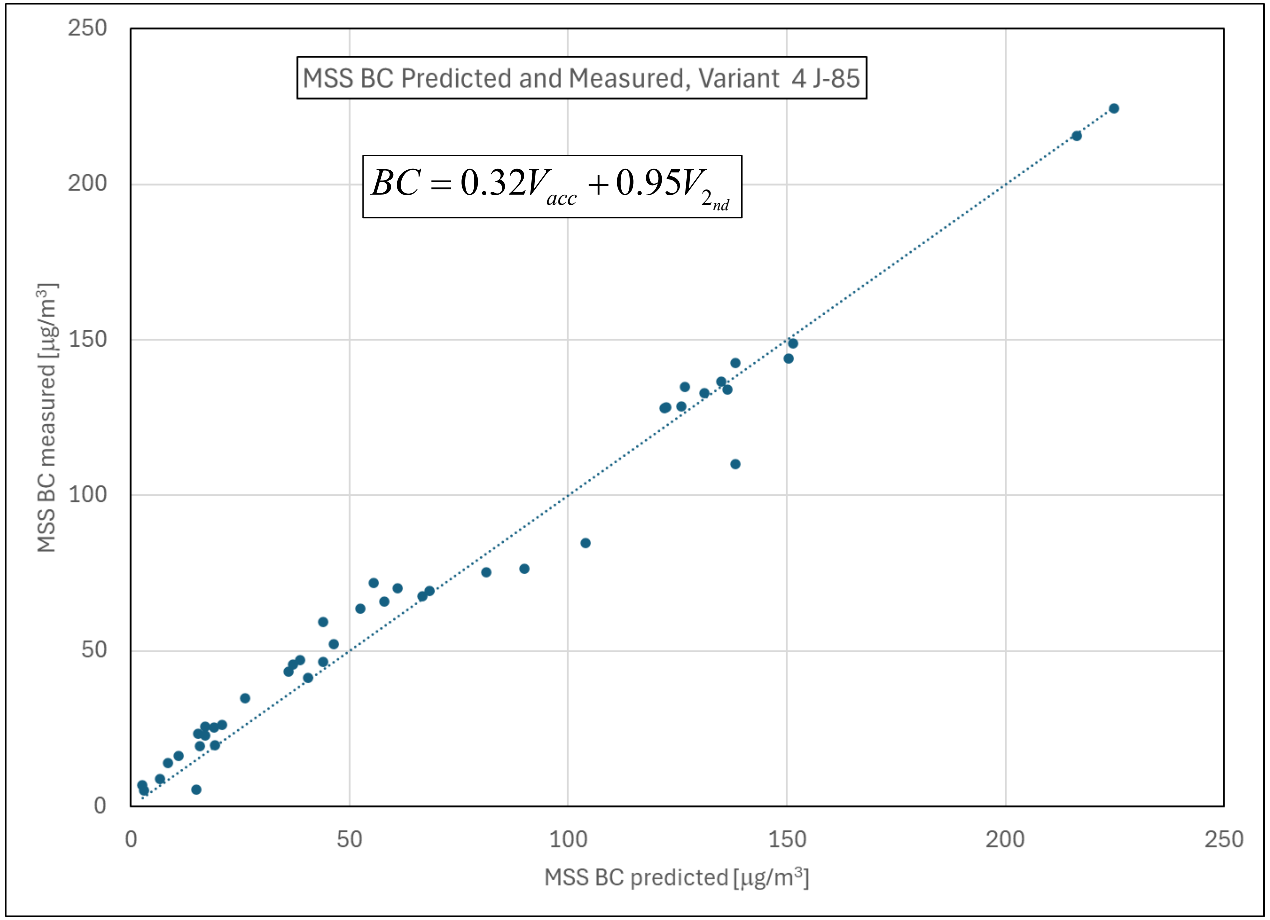
Properties of V150 and V2nd modes different from those of the accumulation mode

- 2-D linear regressions were performed to examine property differences
- Gravimetric Teflon filter mass regressed against Vac and V2nd
- MSS Black Carbon mass regressed against Vac and V2nd
- Results suggest that the physical properties of the accumulation mode and the second mode are quite different.

2-dimensional fit of Teflon Filter Mass



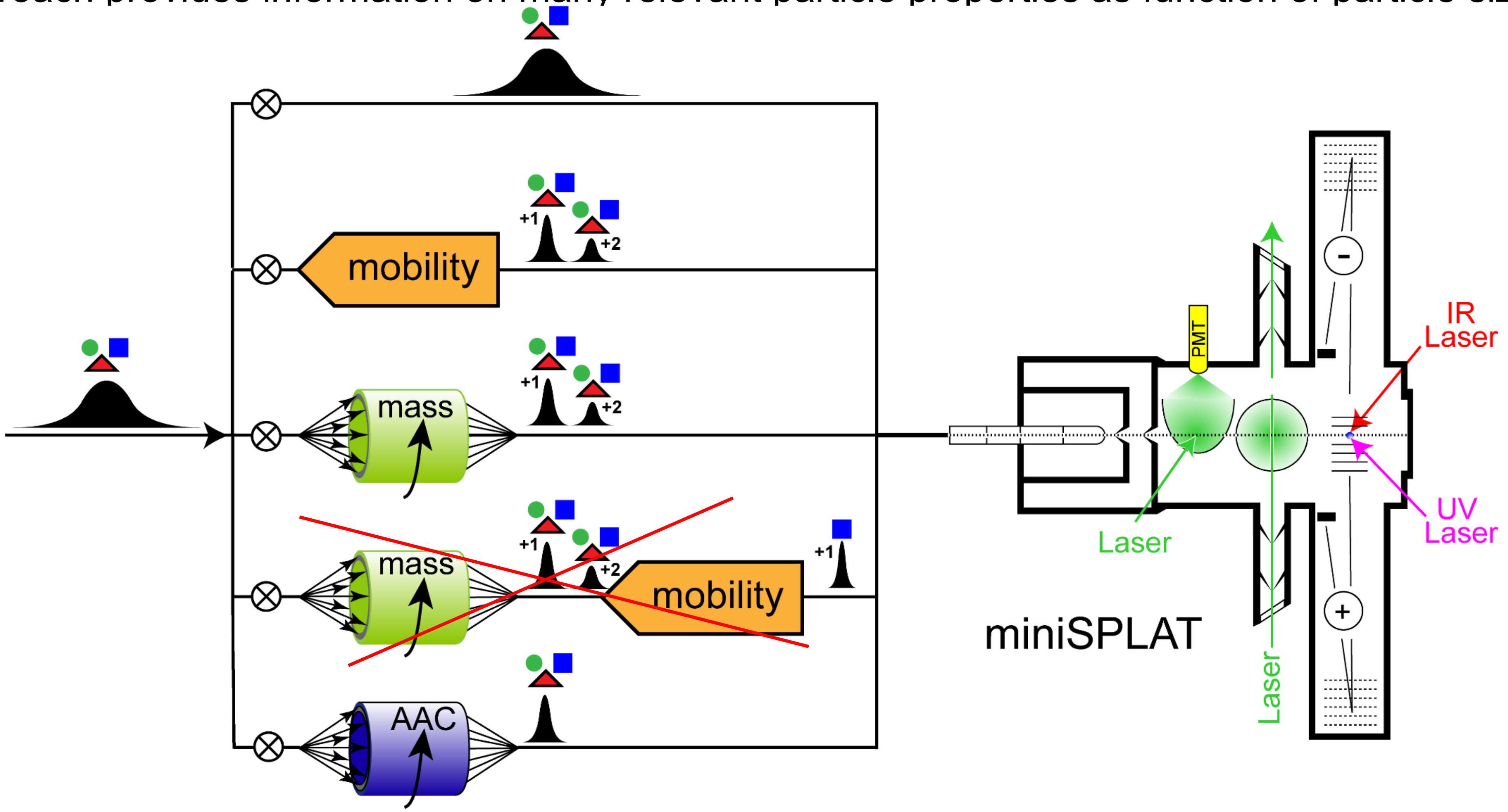
2-Dimensional fit of MSS BC



Physical and chemical properties measured at PNNL with a miniSPLAT

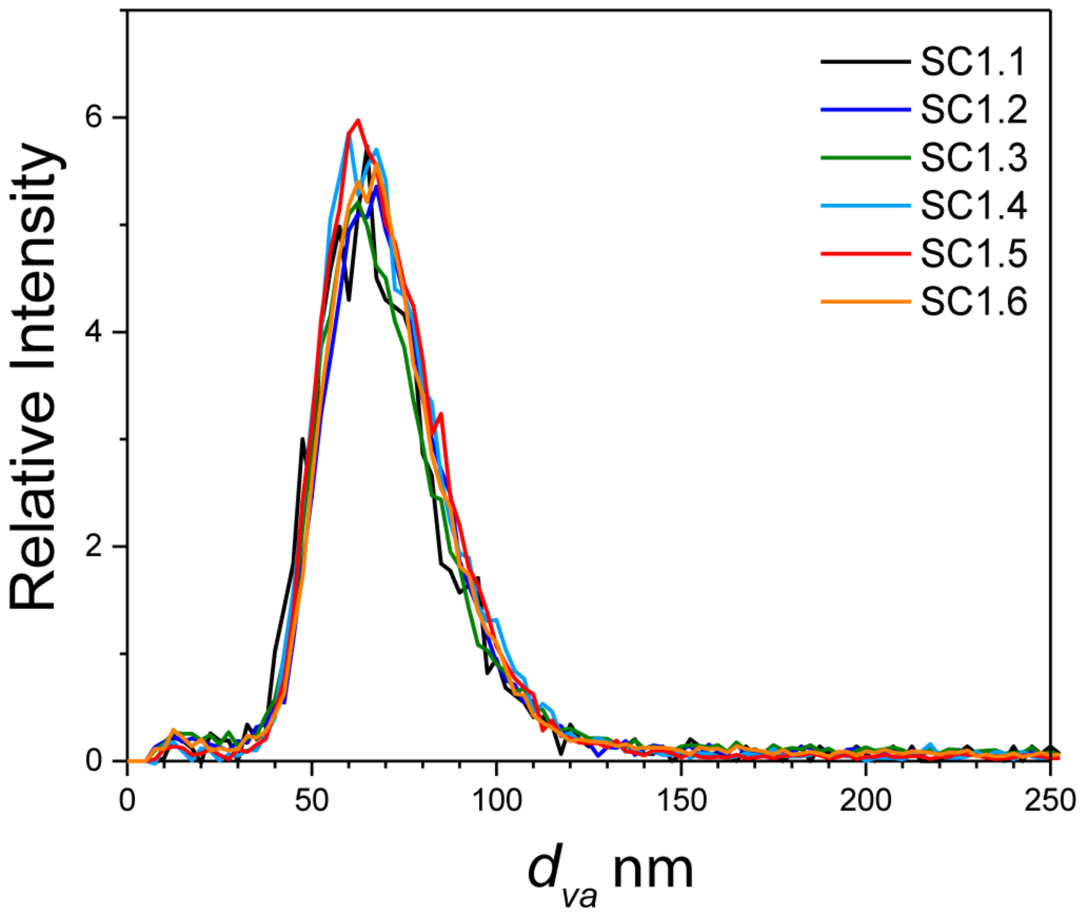
Multidimensional Single Particle Characterization

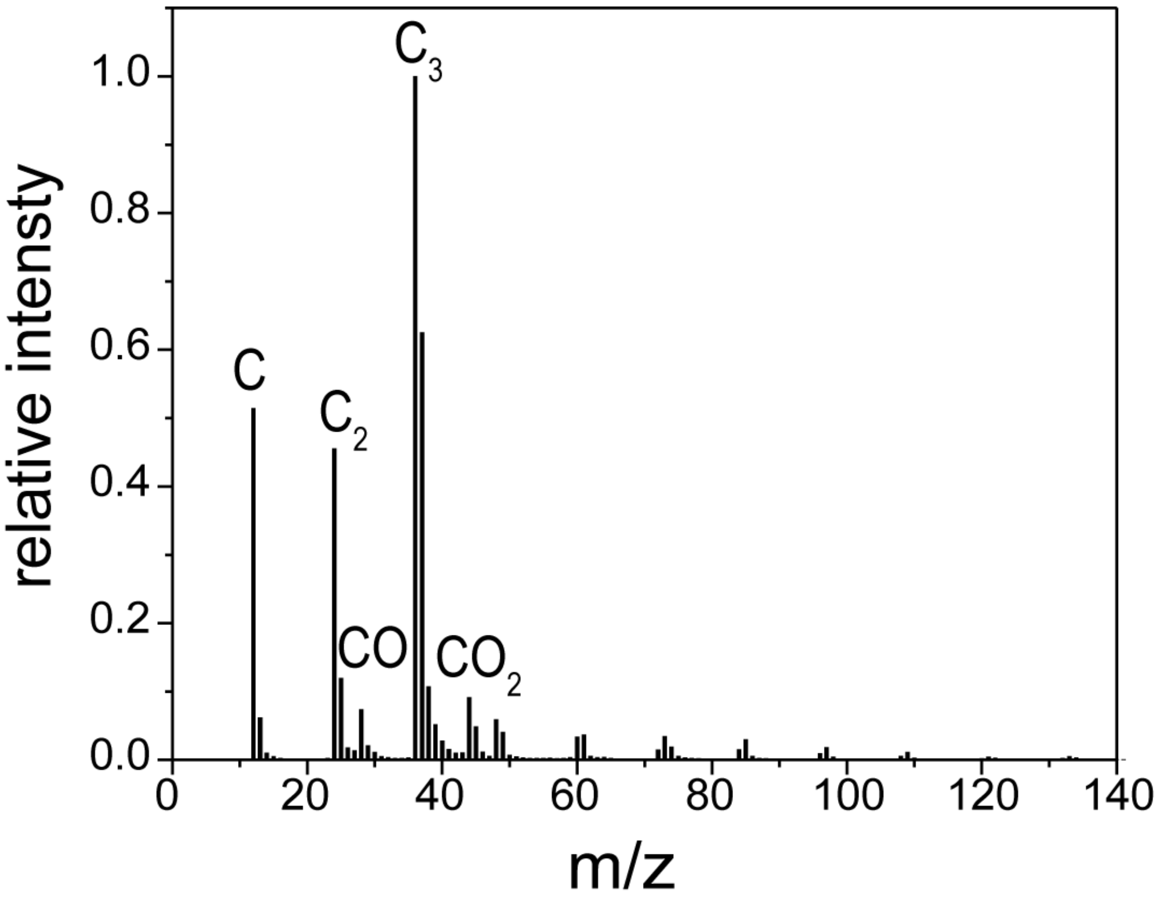
- miniSPLAT measures the vacuum aerodynamic diameter (d_{va}) and composition (*MS*) of all individual particles *and* particles with narrow distributions of properties (mobility diameter, mass, mass & shape, and aerodynamic diameter)
- This approach provides information on many relevant particle properties as function of particle size



VARIAnT4: LGT-60 Turbine-powered Start Cart

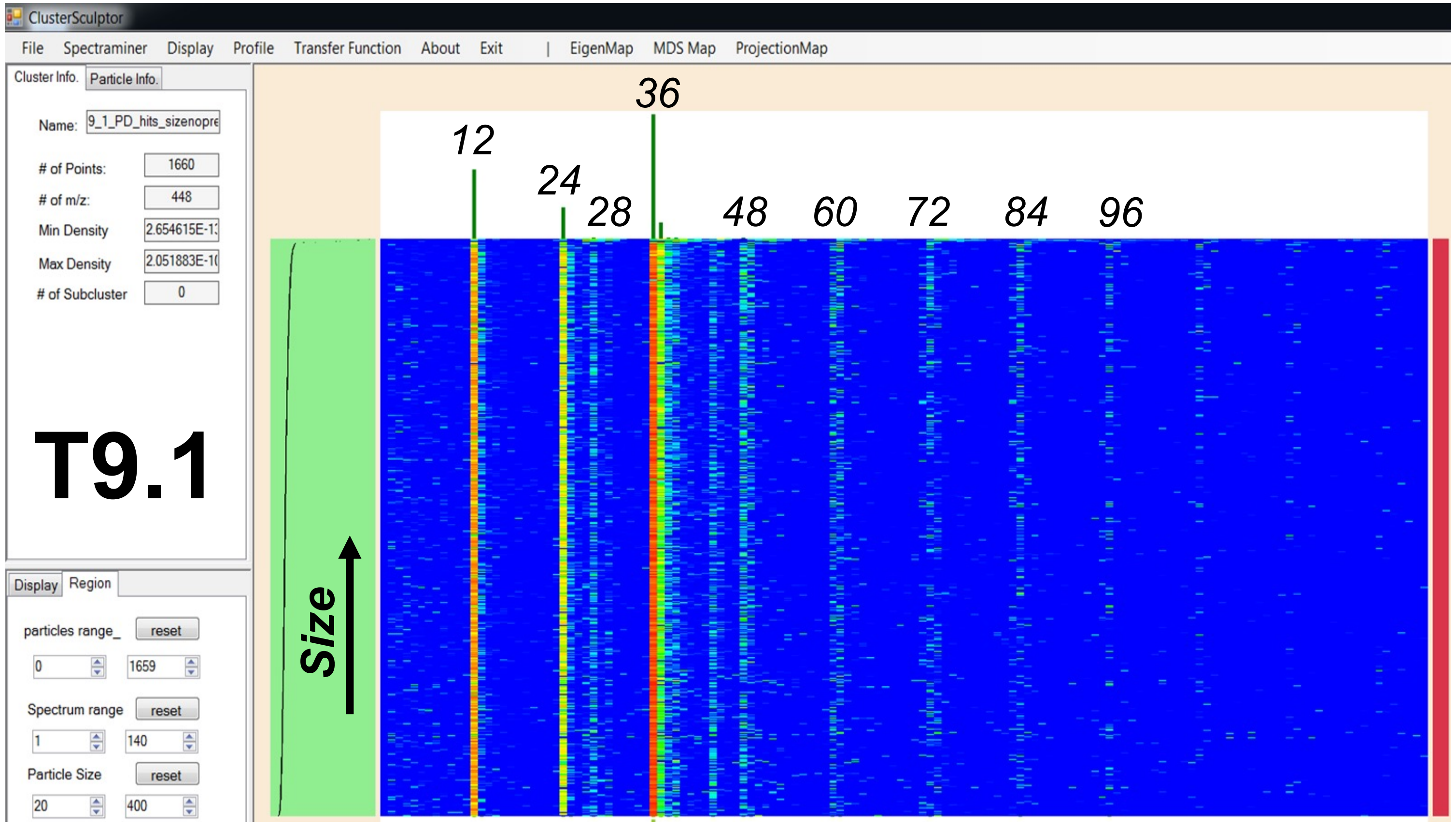
- “Single mode” d_{va} size distributions that peak at ~ 66 nm
- The vast majority of particles emitted by start card (SC1.x, no load) are fractal soot particles composed of EC with small amount of OC (mostly oxygenated organics)
- MS are virtually independent of particles size and mass, including small particles hit in “random-firing” mode

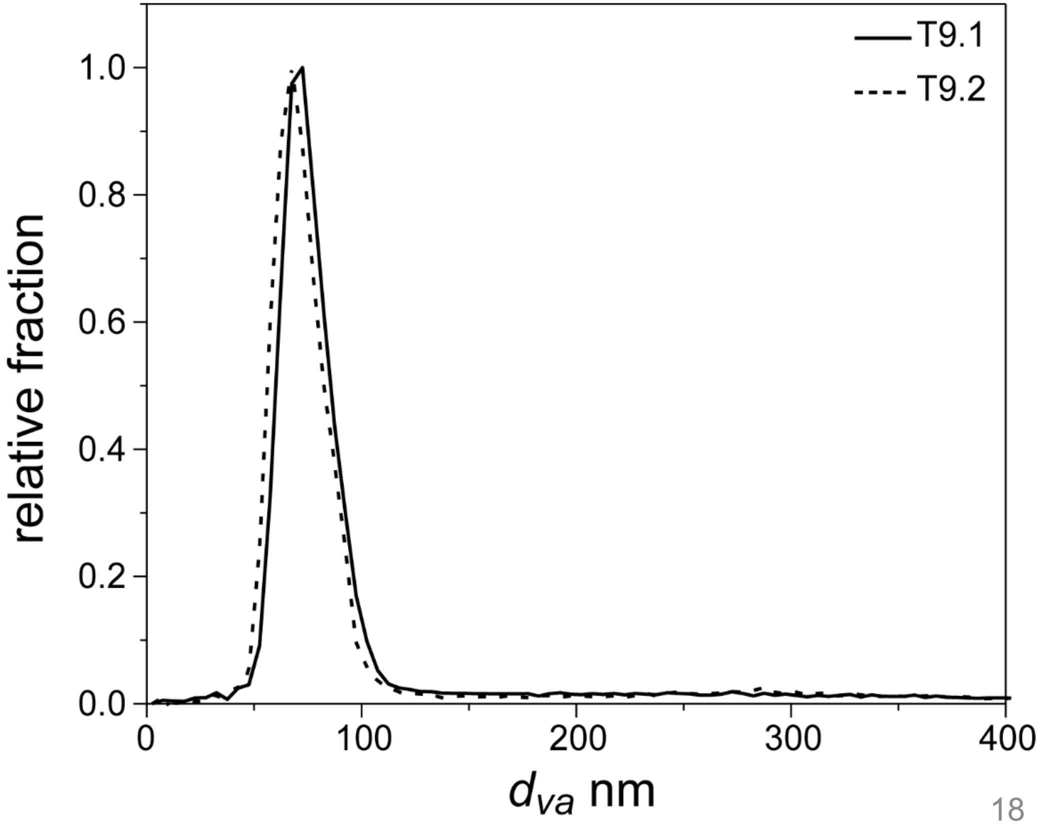




VARIAnT4: J-85, Jet A, PLA 90 (T9.1, T9.2)

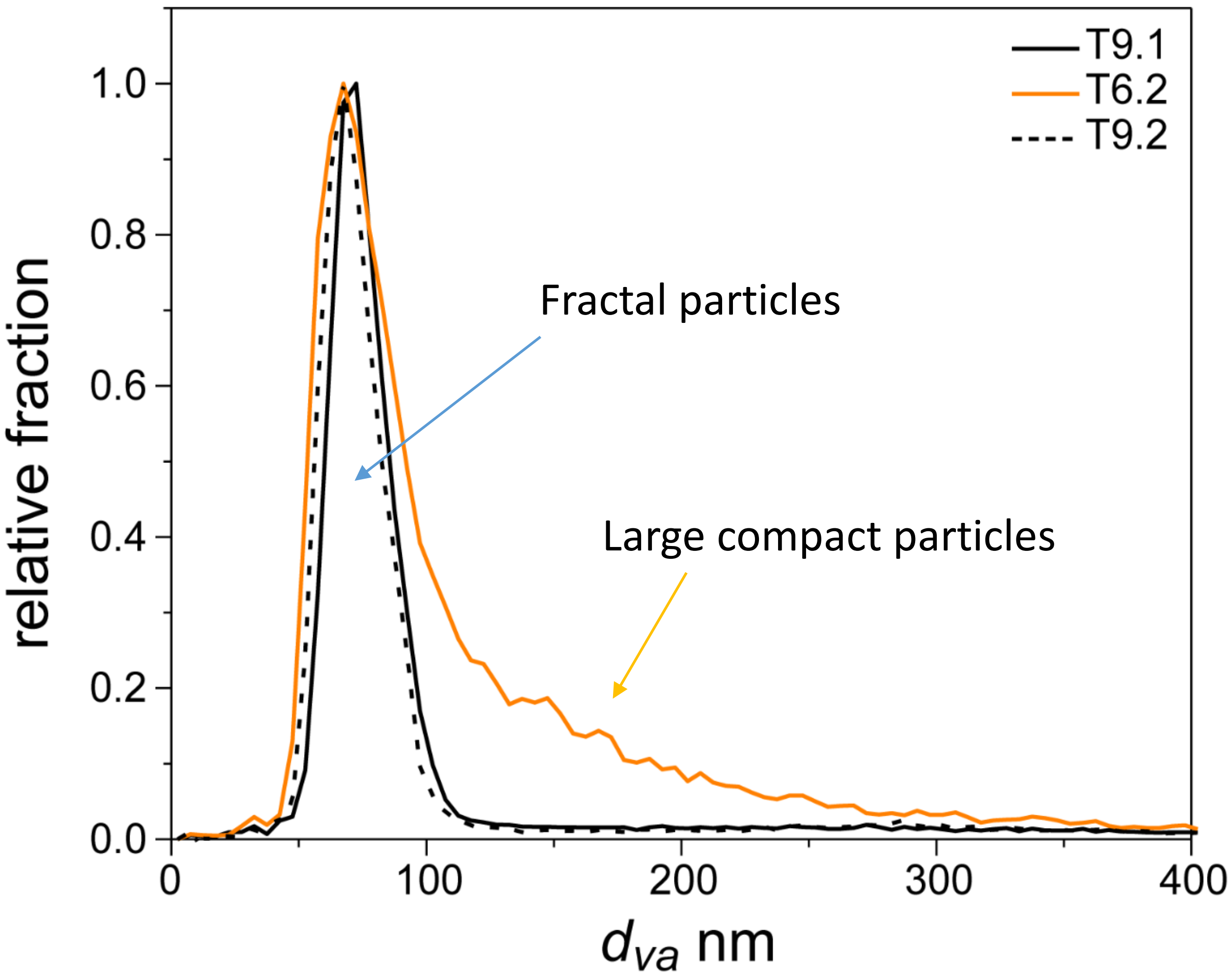
- "Single mode" d_{va} size distributions that peaks at 67 and 71 nm
- Mass spectra of individual particles visualized using Cluster Sculptor and organized by particle size, d_{va}, show that MS are virtually independent of particle size and dominated by C_n^+ ions
- The majority of particles emitted by jet engine under 2 high load conditions (PLA 90) are fractal soot particles composed of EC with small amount of OC

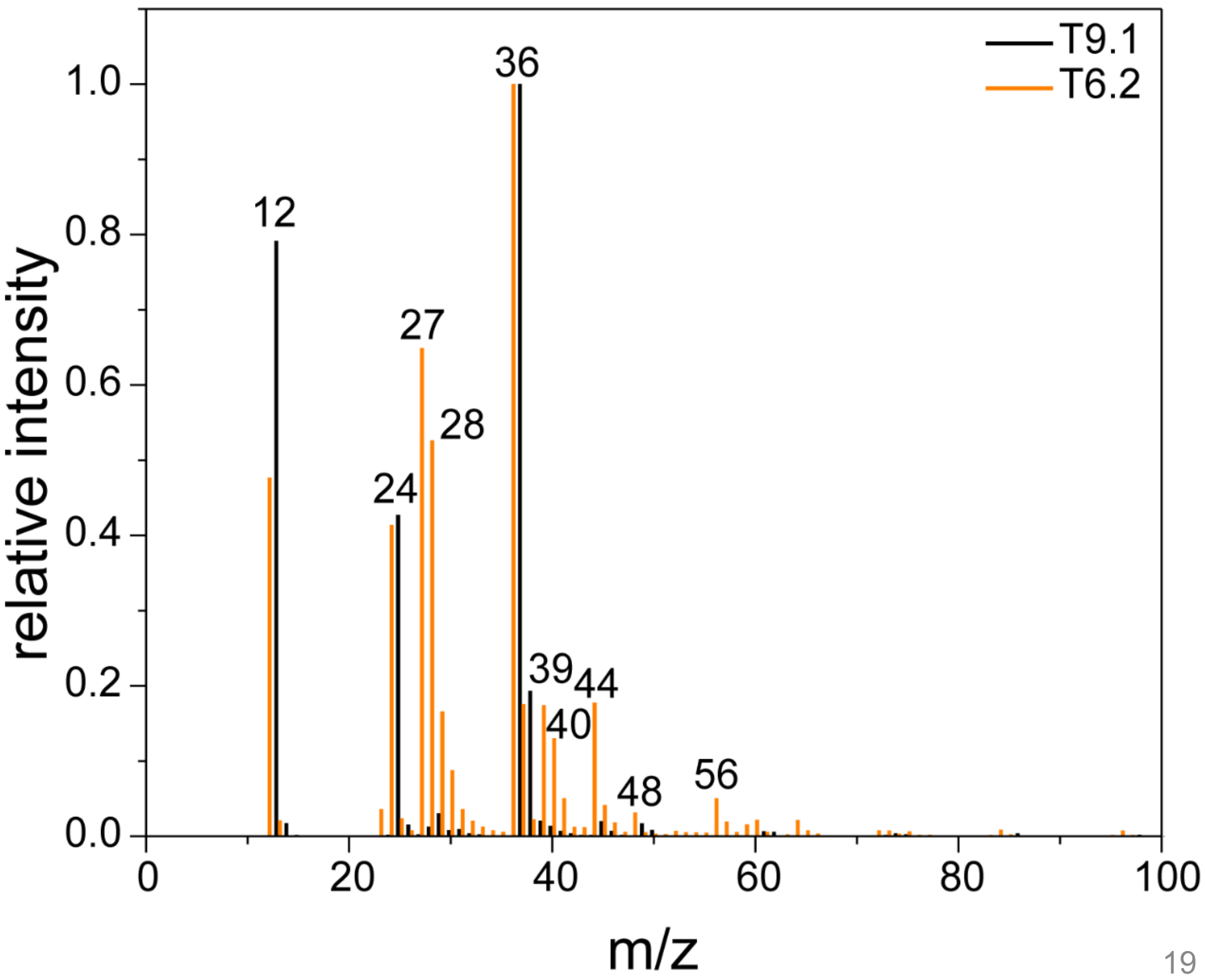




VARIAnT4: J-85, Jet A, PLA 90 (T.6.2, T9.1, T9.2)

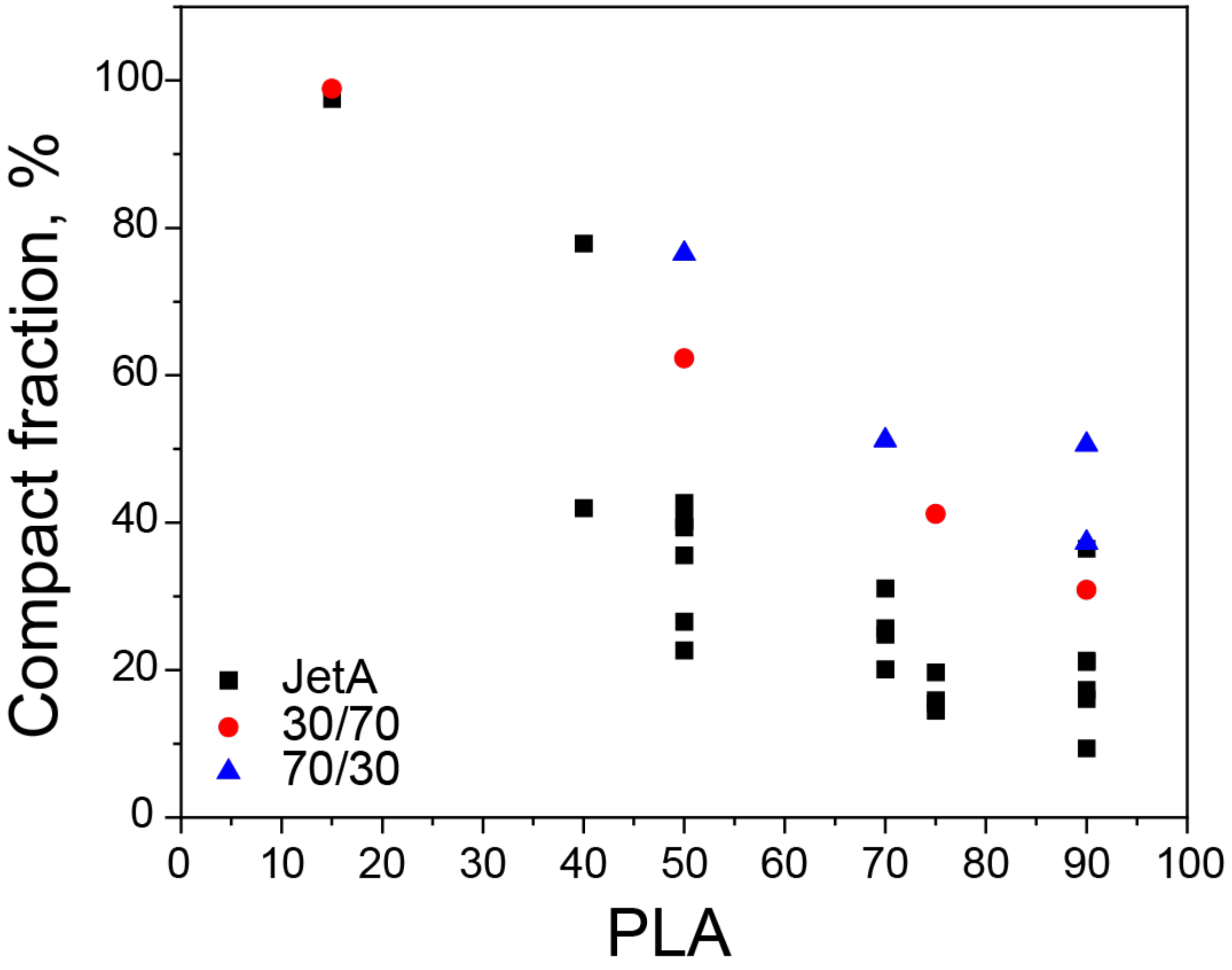
- Not all Jet A, PLA 90 runs are the same
- Particles with larger d_{va} were observed in some PLA 90 runs
- Larger particles contain larger fraction of organics and ash (Ca^+, CaO^+, Zn^+ ions)

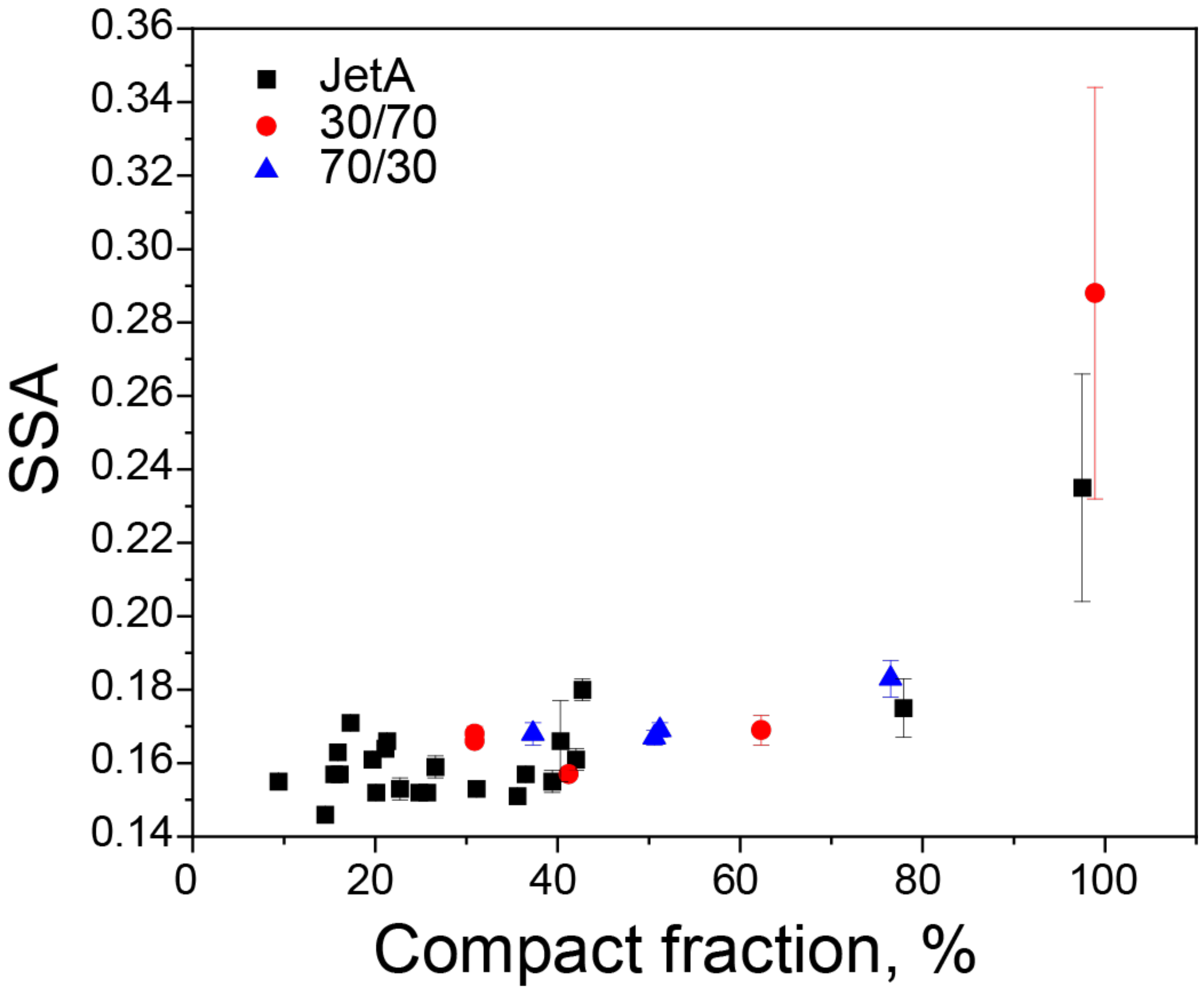




VARIAnT 4: J-85, Jet-A and Camelina Blends

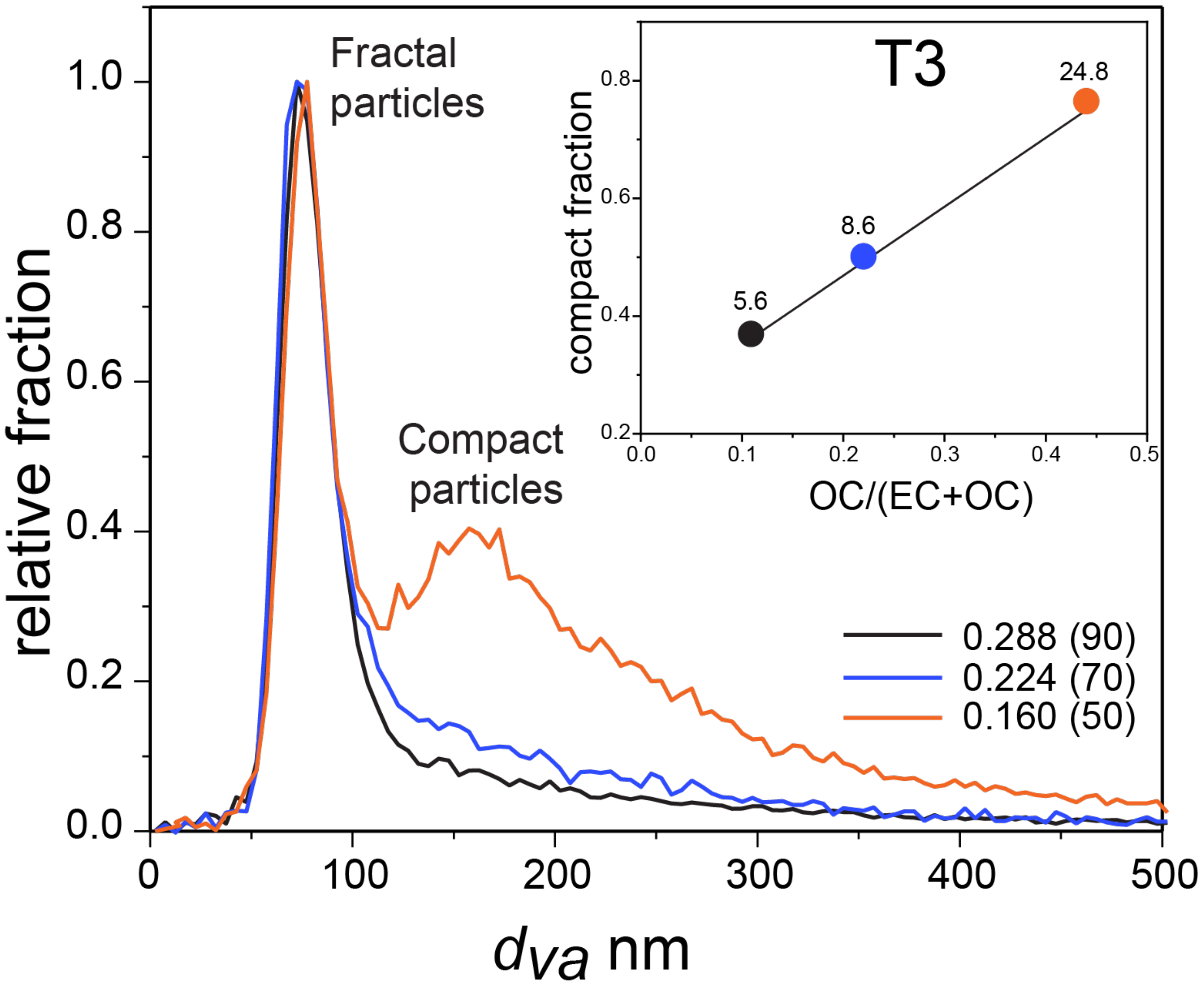
- Faction of compact particles increases with decreasing PLA was observed for all fuels
- Compact particles with larger d_{va} are less absorbing and higher values of Single Scattering Albedo (SSA) measured by CAPS

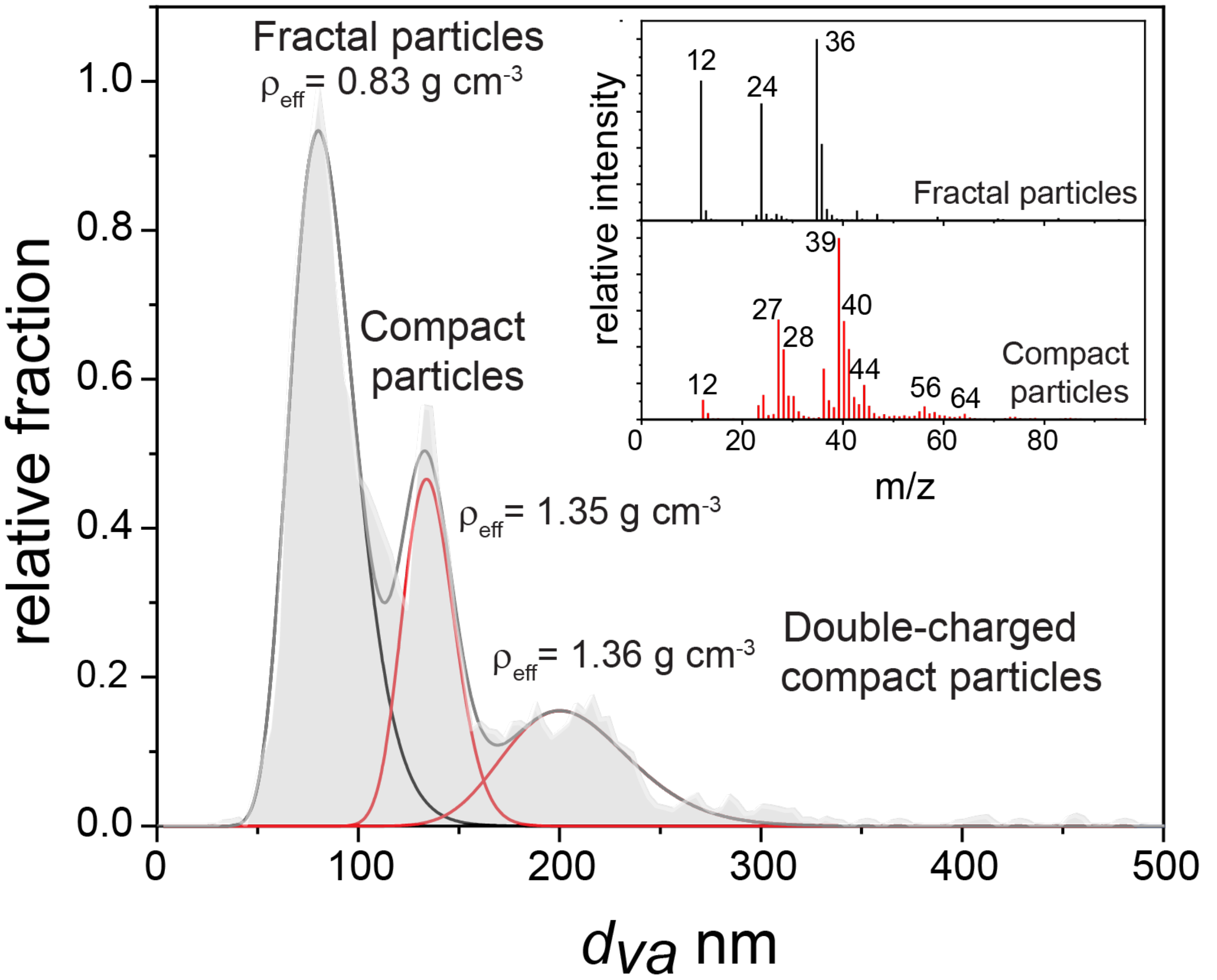




VARIAnT4: J-85, 70% Cam / 30% Jet A, Different PLA

- Faction of compact particles increases with decreasing PLA was observed for all fuels
- Particles with larger d_{va} contain larger fraction of organics and ash, have higher mass and higher effective density

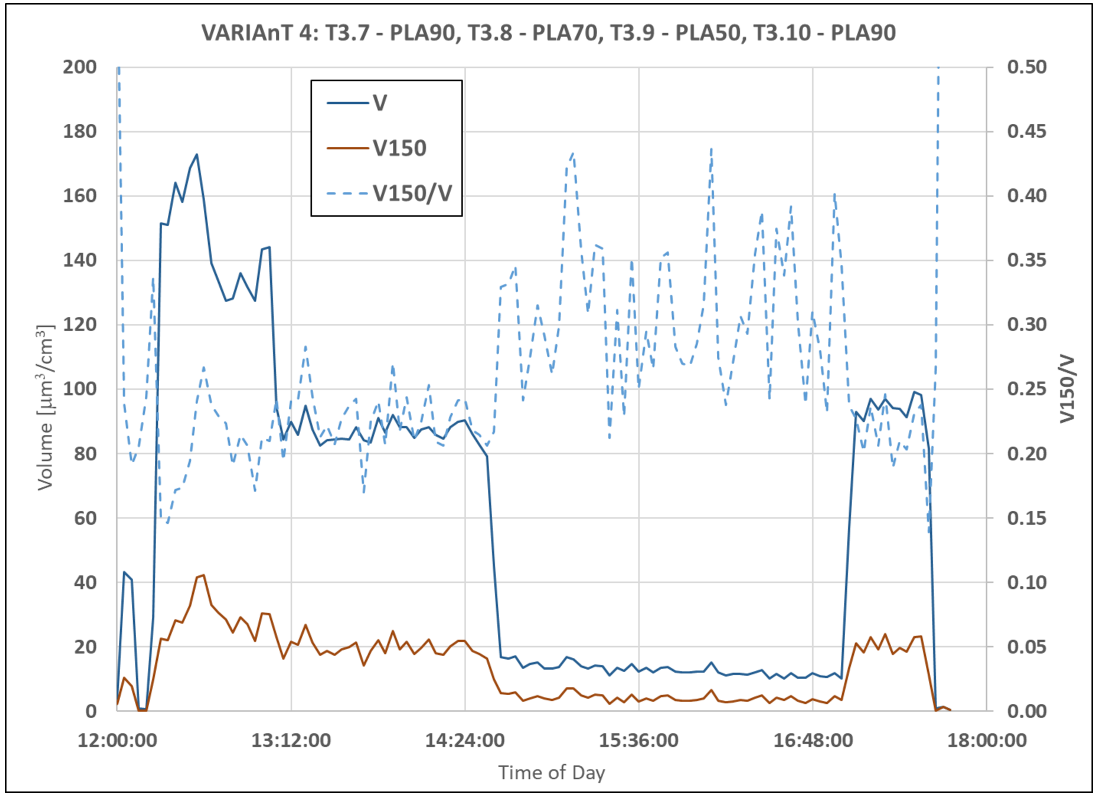


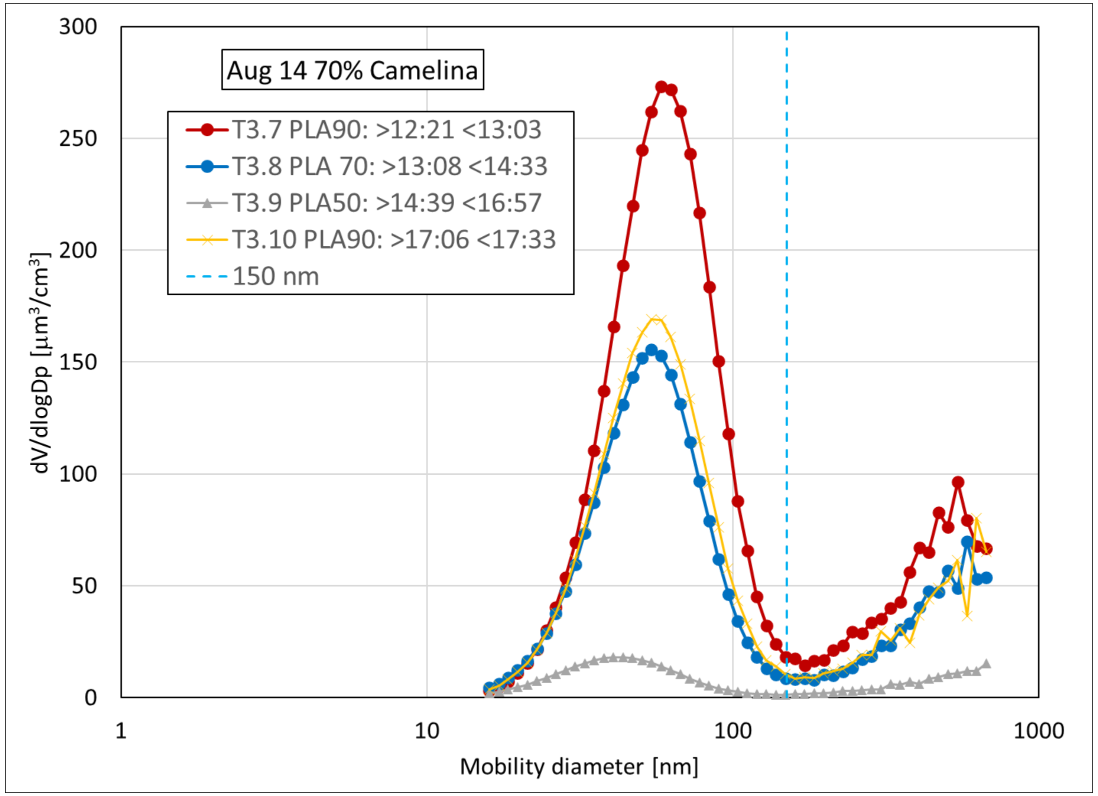


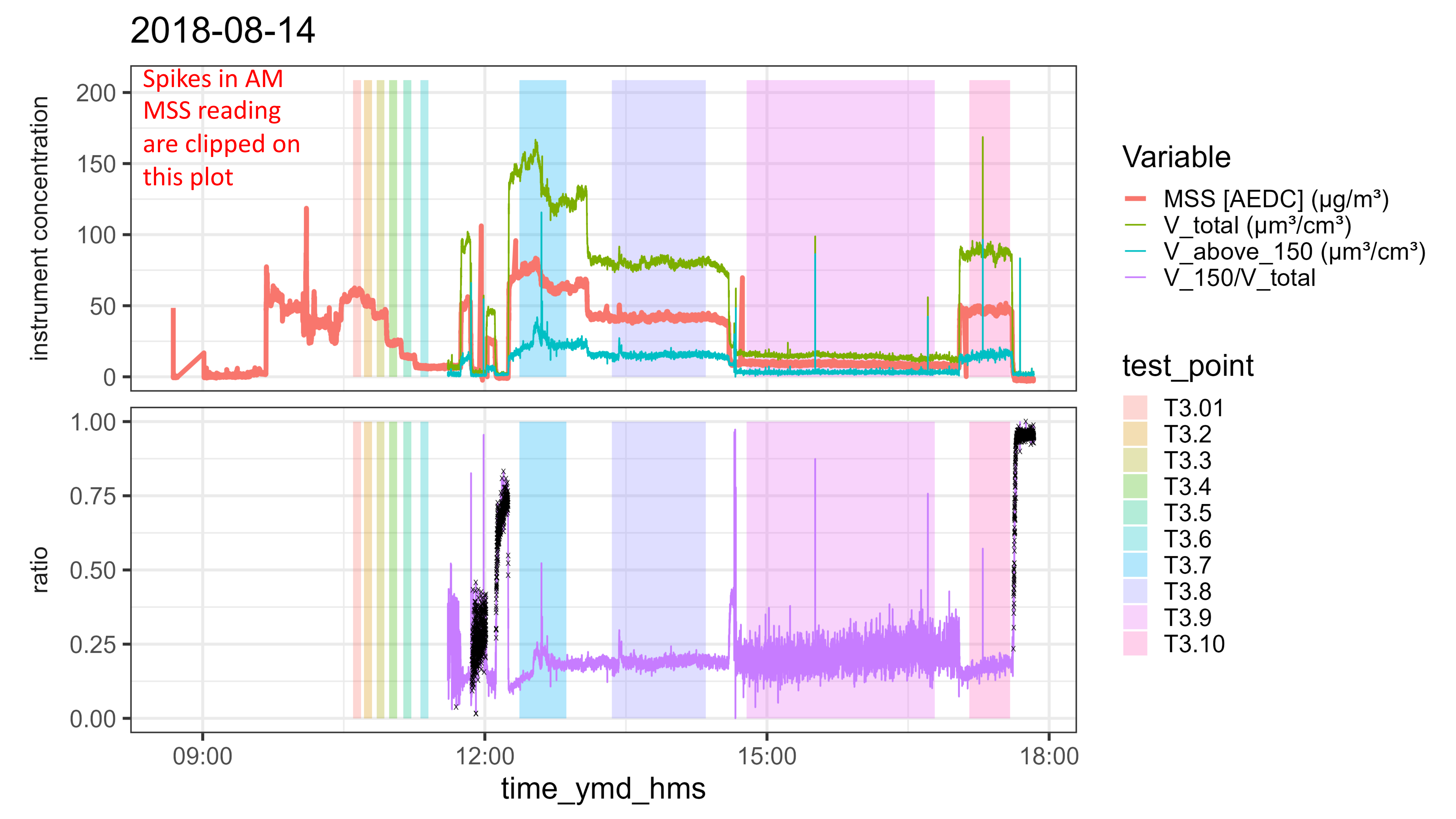
Are these particles real or sampling artifact?

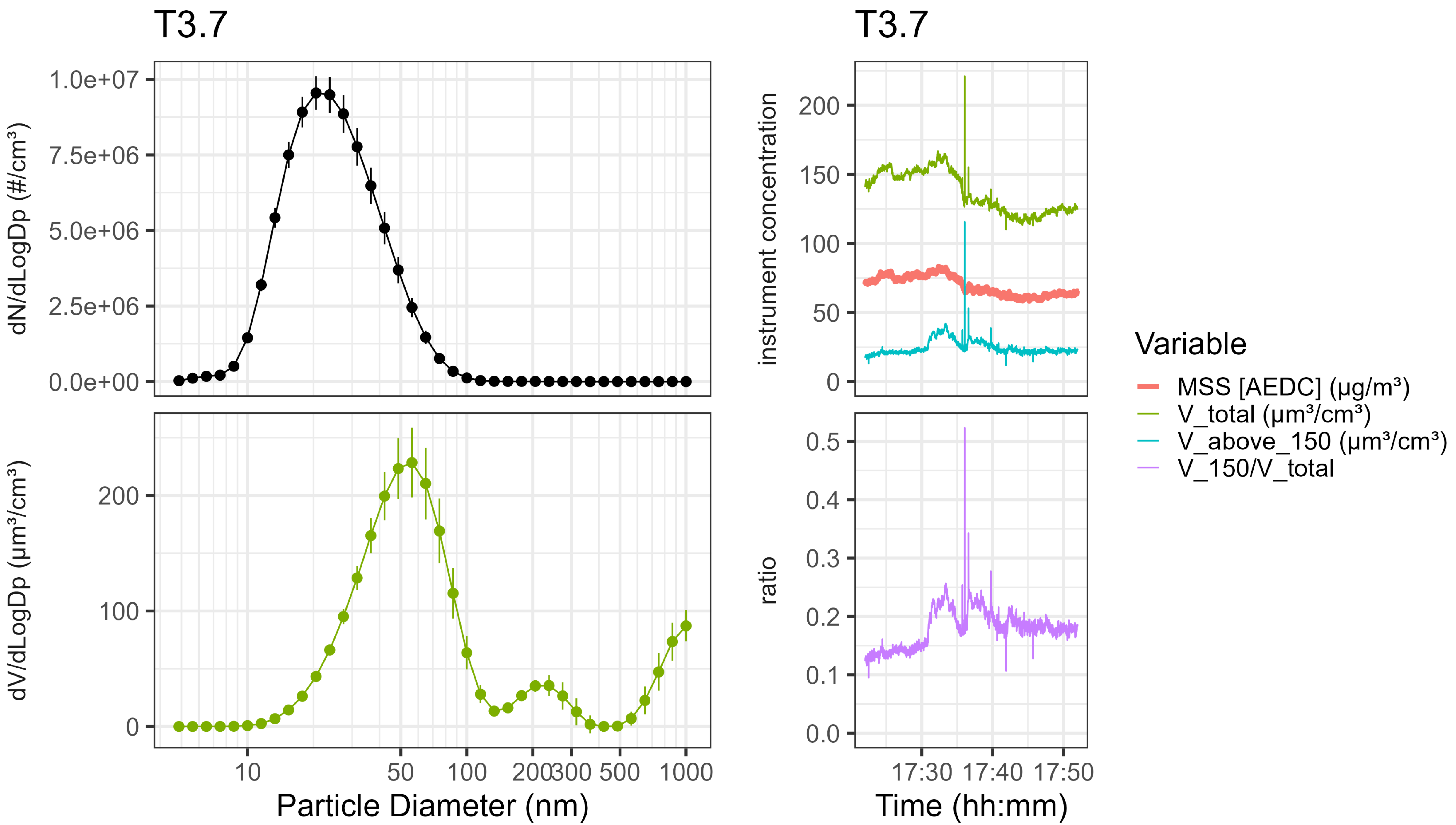
- Work elsewhere suggests that these larger particles result from deposition, re-entrainment from engine, sampling system surfaces
- We saw no evidence of that behavior

VARIAnT 4 Series T3.x J-85 70% Camalina

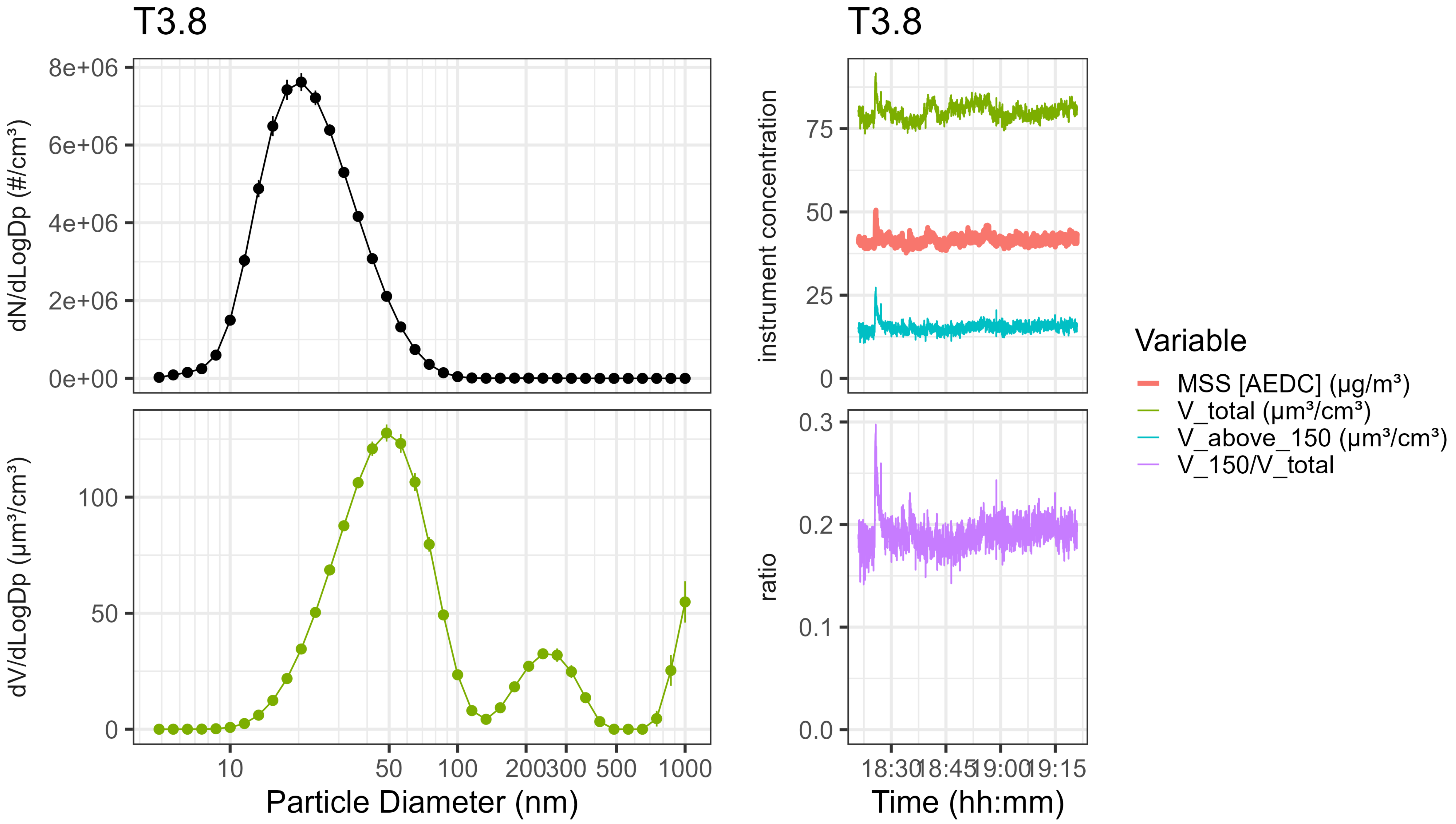





2018-08-14
Spikes in AM MSS reading are clipped on this plot
instrument concentration
200
150
100
50
0
ratio
1.00
0.75
0.50
0.25
0.00
09:00
12:00
15:00
18:00
time_ymd_hms
Variable
MSS [AEDC] (μg/m³)
V_total (μm³/cm³)
V_above_150 (μm³/cm³)
V_150/V_total
test_point
T3.01
T3.2
T3.3
T3.4
T3.5
T3.6
T3.7
T3.8
T3.9
T3.10



T3.7
T3.7
dN/dLogDp (#/cm³)
1.0e+07
7.5e+06
5.0e+06
2.5e+06
0.0e+00
dV/dLogDp (µm³/cm³)
200
100
0
10
50
100
200
300
500
1000
Particle Diameter (nm)
instrument concentration
200
150
100
50
0
ratio
0.5
0.4
0.3
0.2
0.1
0.0
17:30
17:40
17:50
Time (hh:mm)
Variable
MSS [AEDC] (µg/m³)
V_total (µm³/cm³)
V_above_150 (µm³/cm³)
V_150/V_total


T3.8
T3.8
8e+06
6e+06
4e+06
2e+06
0e+00
dN/dLogDp (#/cm³)
100
50
0
dV/dLogDp (µm³/cm³)
10
50
100
200
300
500
1000
Particle Diameter (nm)
instrument concentration
75
50
25
0
ratio
0.3
0.2
0.1
0.0
18:30
18:45
19:00
19:15
Time (hh:mm)
Variable
MSS [AEDC] (µg/m³)
V_total (µm³/cm³)
V_above_150 (µm³/cm³)
V_150/V_total

Conclusions

- Under some conditions, especially at low loads, when soot concentrations were low, we observed a distinct size mode, a "2^{nd} mode", consisting of particles larger than ~ 150 nm mobility diameter
- The 2^{nd} mode is not a sampling artifact: no evidence for mechanical generation by particle shedding from the sampling system as demonstrated during the daily zero checks of the system and response to step changes in load
- Observed in four independent test programs (2014-2018) using a variety of metrics
    - PSDs with SMPSs (6-225 and 15-690 nm), DMS500 (5-1000 nm), EEPS (6-560 nm)
    - Other particle metrics including total filter mass, MSS BC, EC, OC, and CAPS PMSSA that measures light extinction and scattering, SSA

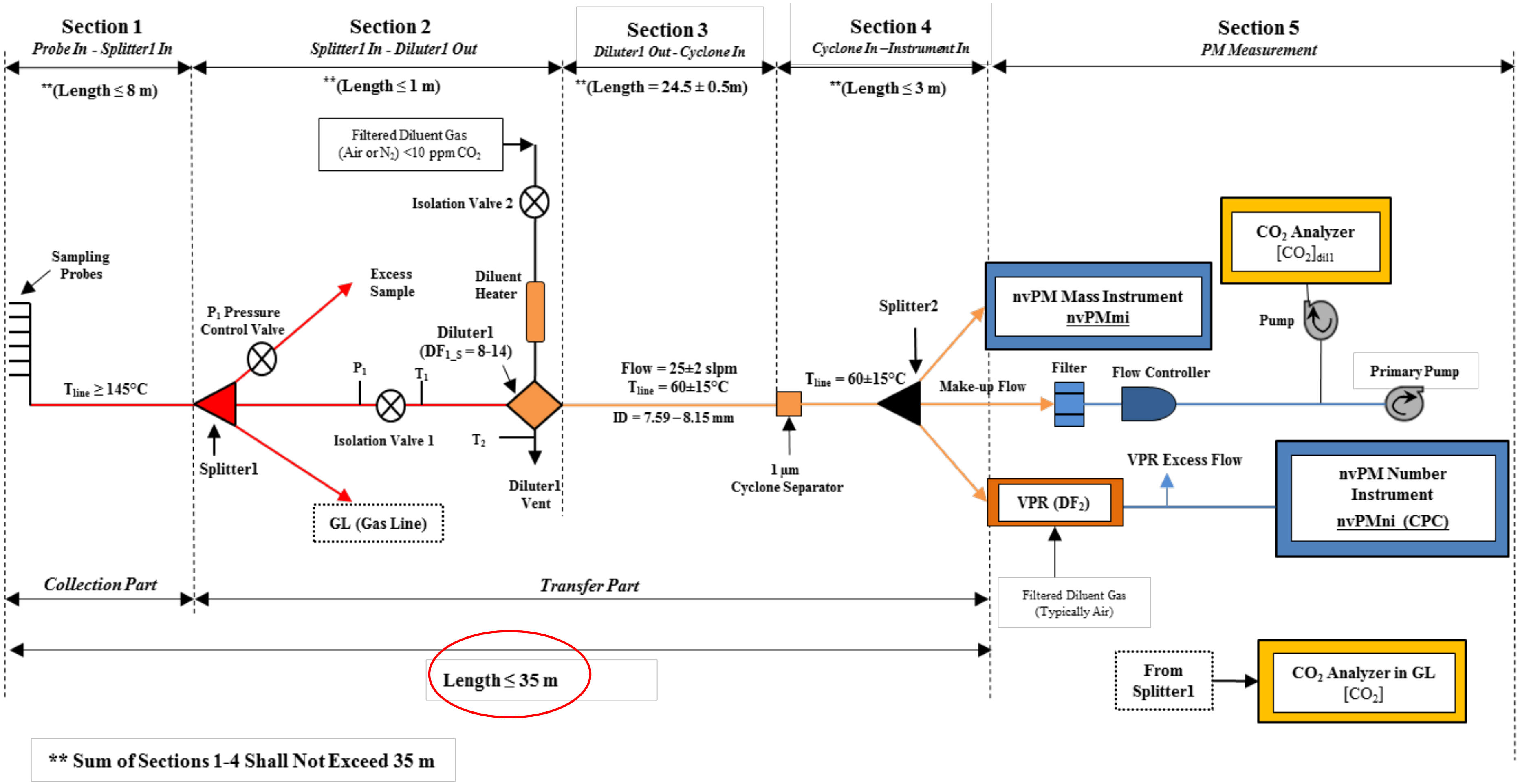
Conclusions

- The accumulation and 2nd modes have different physical properties, density, light absorption, SSA
- In the most recent study, VARIAnT 4 (2018), a miniSPLAT single particle mass spectrometer was used to determine composition, effective density/morphology of compact vs fractal
  - Accumulation mode particles were found to contain mainly fractal soot with some OC. Mass spectra showed mainly carbon peaks
  - 2nd mode particles were more compact and denser. Mass spectra was more complex with peaks associated with carbon and ash (Ca, Zn compounds)
- ***We still don't understand how they form***

Thank you

Long sampling lines suppress nucleation mode formation and lead to significant particle losses

Recommended aircraft sampling line configuration (SAE International Aerospace Information Report 6241)



Introduction

- Piston engine exhaust particle size distributions (PSD) typically show three distinct modes: a nucleation mode (~3 - 30 nm diameter) mainly of semi-volatile, a soot mode (~30 - 300 nm) mainly carbonaceous aggregates, and a coarse mode (>~500 nm) mechanically generated particles from oil atomization and re-entrainment from in-cylinder and exhaust surfaces.
- Measurement of particles from aircraft gas turbine engines is much more challenging with exhaust temperatures as high as 900 K velocities approaching Mach 1. This necessitates very long sampling lines that adsorb semi-volatile material *suppressing nucleation mode formation*. Aggregates in the soot mode are smaller than from piston engines (~15 to 50 nm) range.
- Compared to piston engines there is less opportunity for the exhaust to interact with surfaces and no piston rings to atomize oil. Thus, coarse particles are not expected to be an issue. However, in four independent test campaigns with a GE J-85 engine and various fuels we have observed a significant volume and mass of non-volatile particles larger than about 150 nm
- What are these particles, how are they produced?