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

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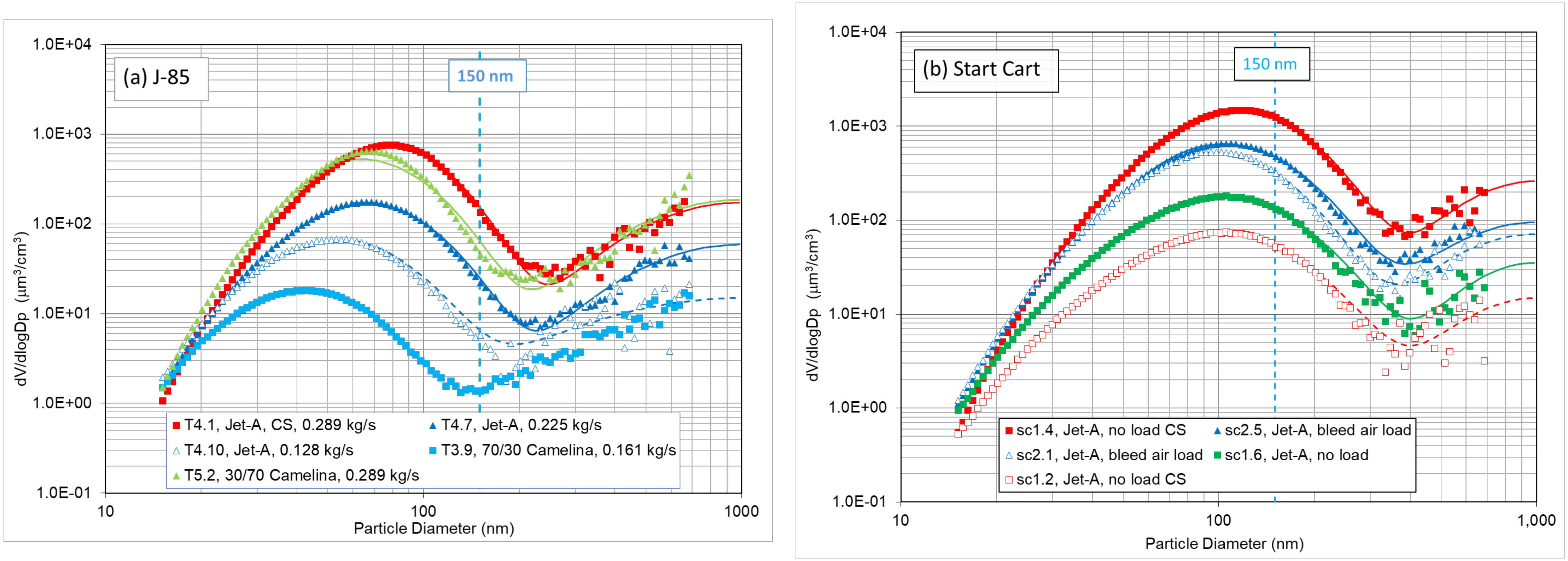
Non-volatile particles for aircraft gas turbines: a Secondary mode mainly above about 150 nm?

- 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

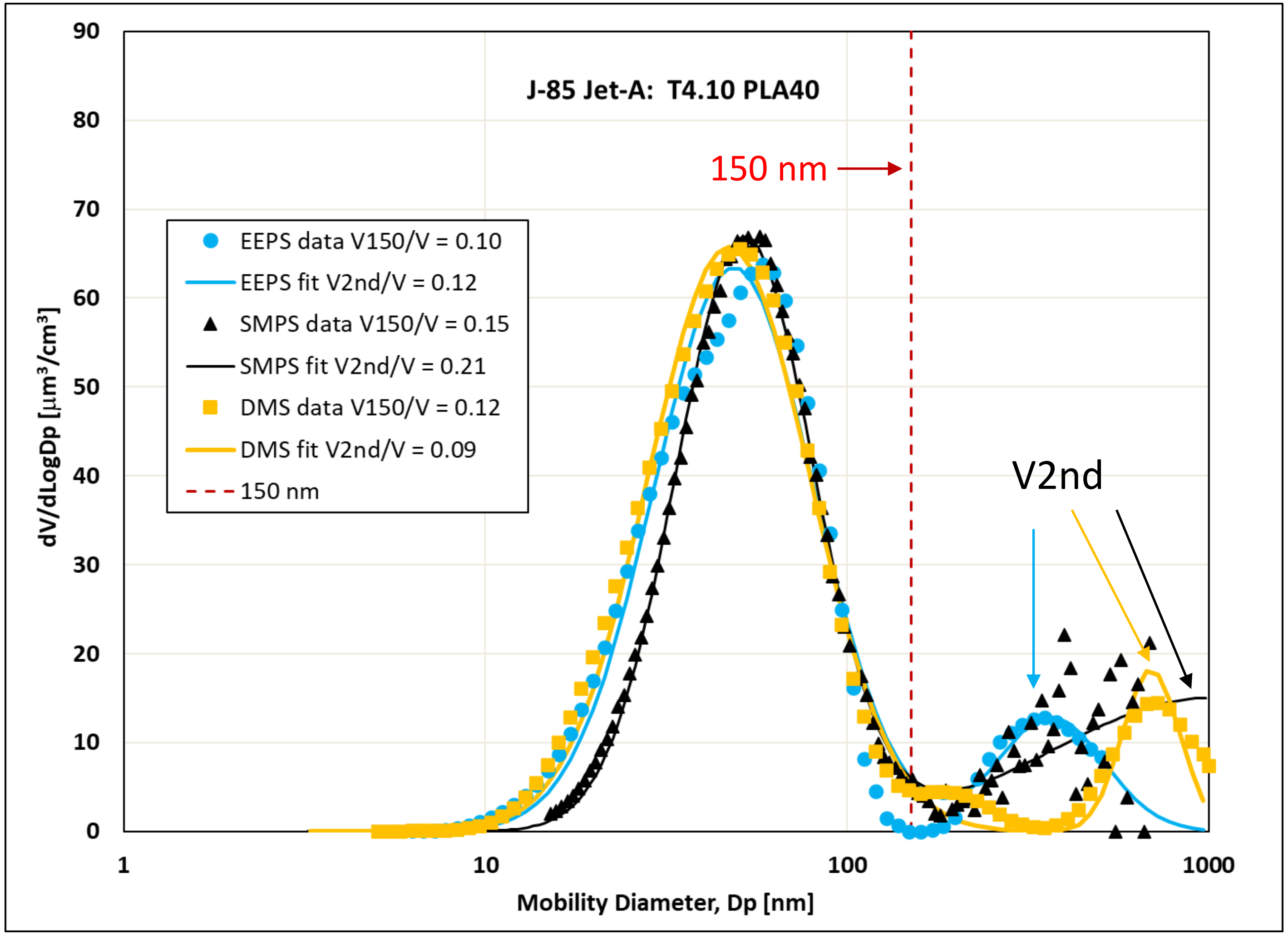
Measured Parameter(s)	Instrument Make/Model	Campaign and Number of Analyzers	
		V3	V4
Total particle mass	Multifilter Sampler w/25-mm Teflon and backup quartz filters	1	1
Black carbon mass concentration	AVL Model 483 Micro Soot Sensor (MSS); 0.001 – 300mg/m^3, detection limit ~0.005 mg/m^3	1	1
	AVL Model 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 volume distributions for J-85 and Start Cart with bimodal fits to the accumulation mode and 2nd modes

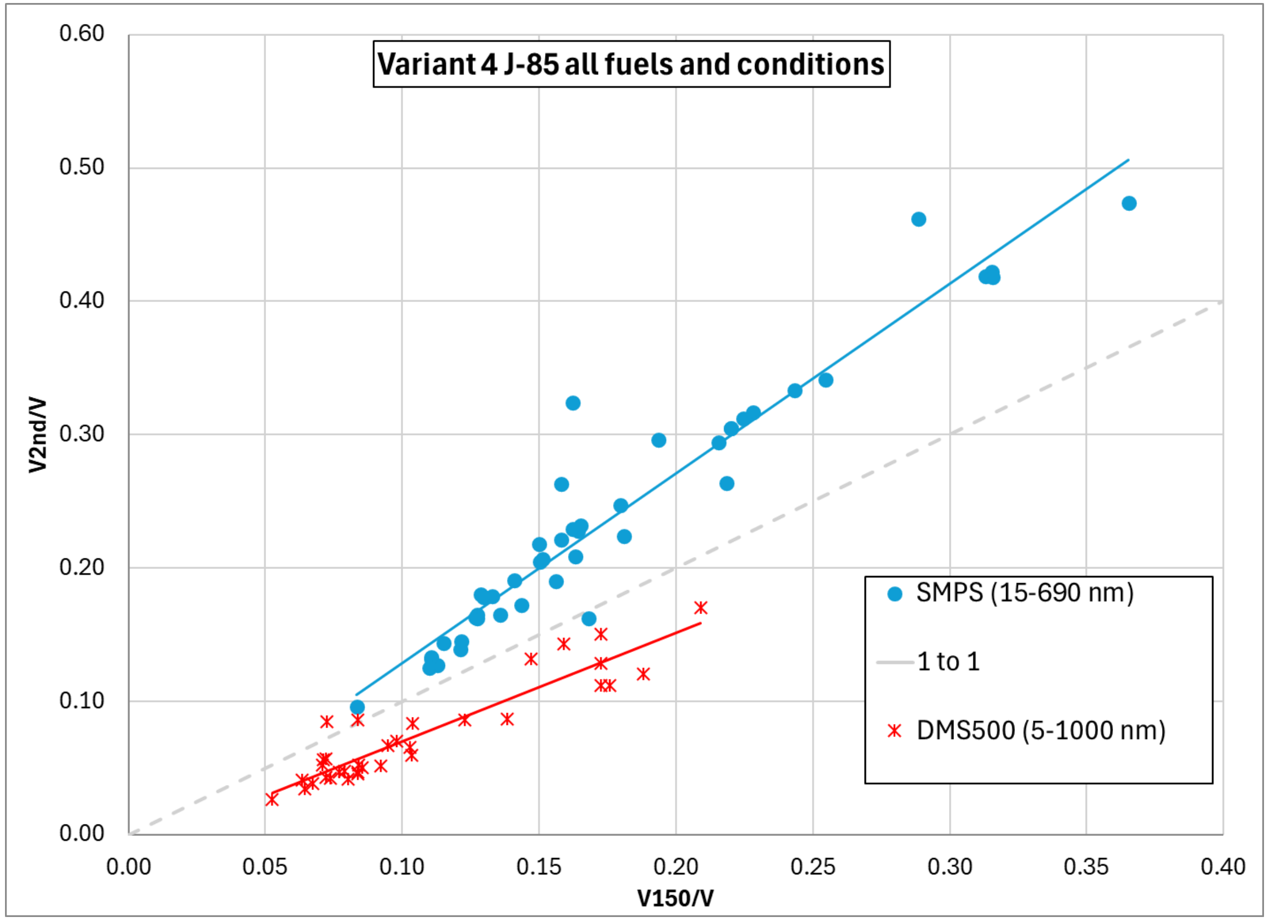


J-85 the saddle point between the modes shifts right and V2nd/V decreases with increasing load. Start Cart accumulation mode particles are larger and the position of saddle point essentially constant ~ 400 nm with volume fraction in the 2nd mode smaller and insensitive to test conditions.

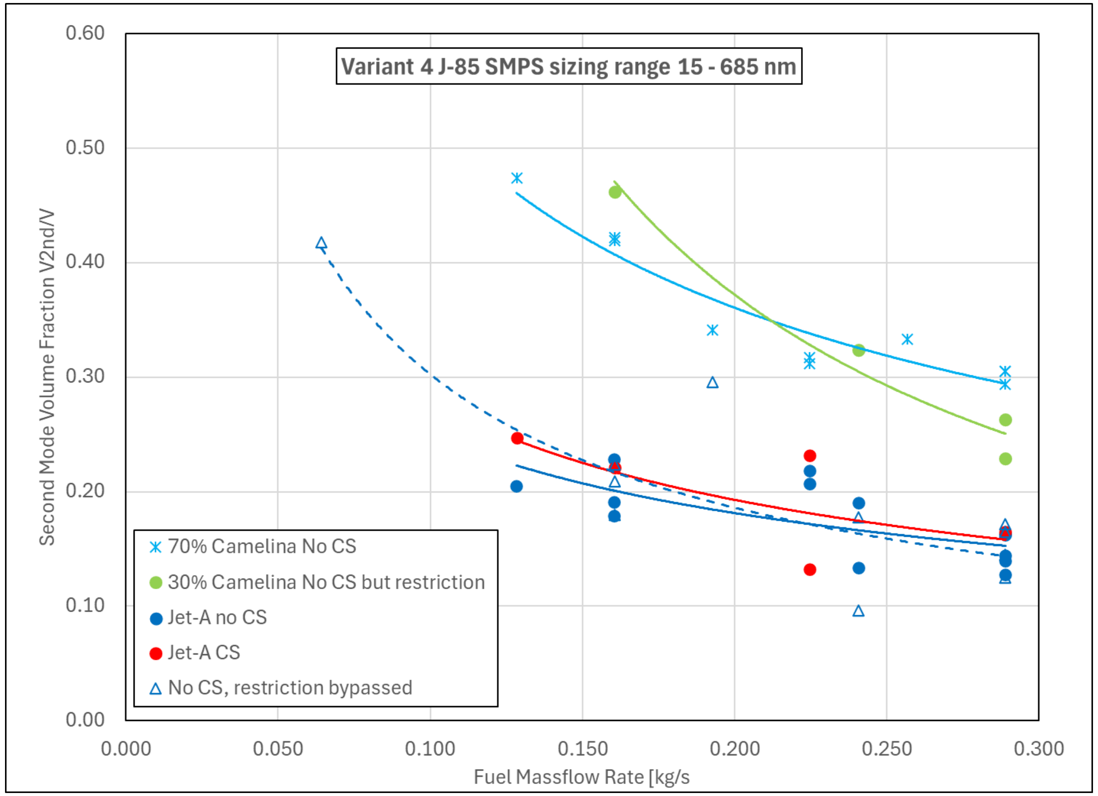
Comparing V150 and V2nd (fit): EEPS (6-560 nm), SMPS (15-690 nm), DMS (5-1000 nm)

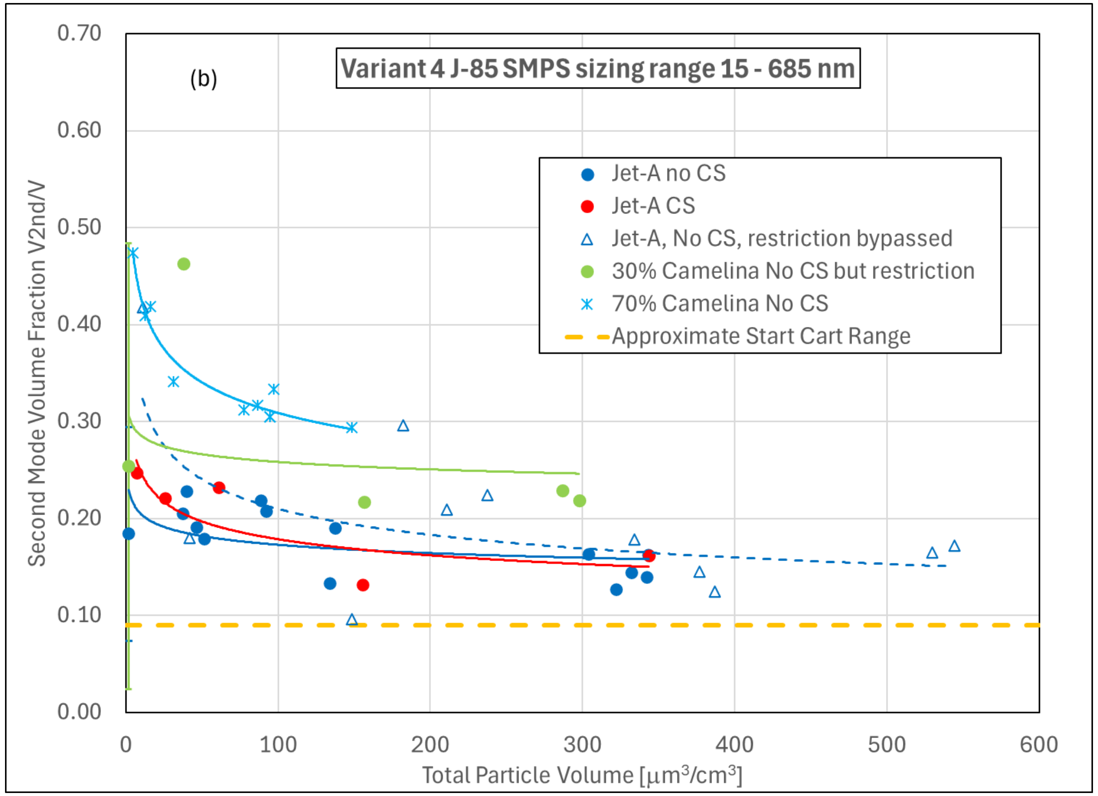


V2nd vs V150: larger slope and values for SMPS than for DMS500 but similar trends

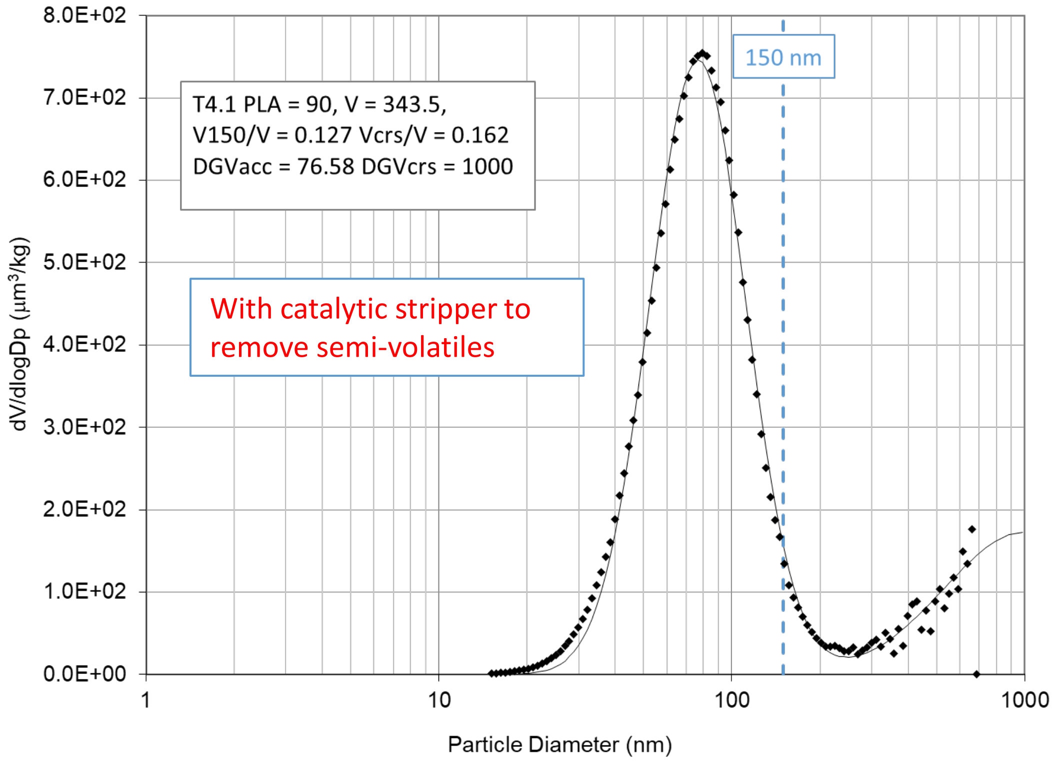


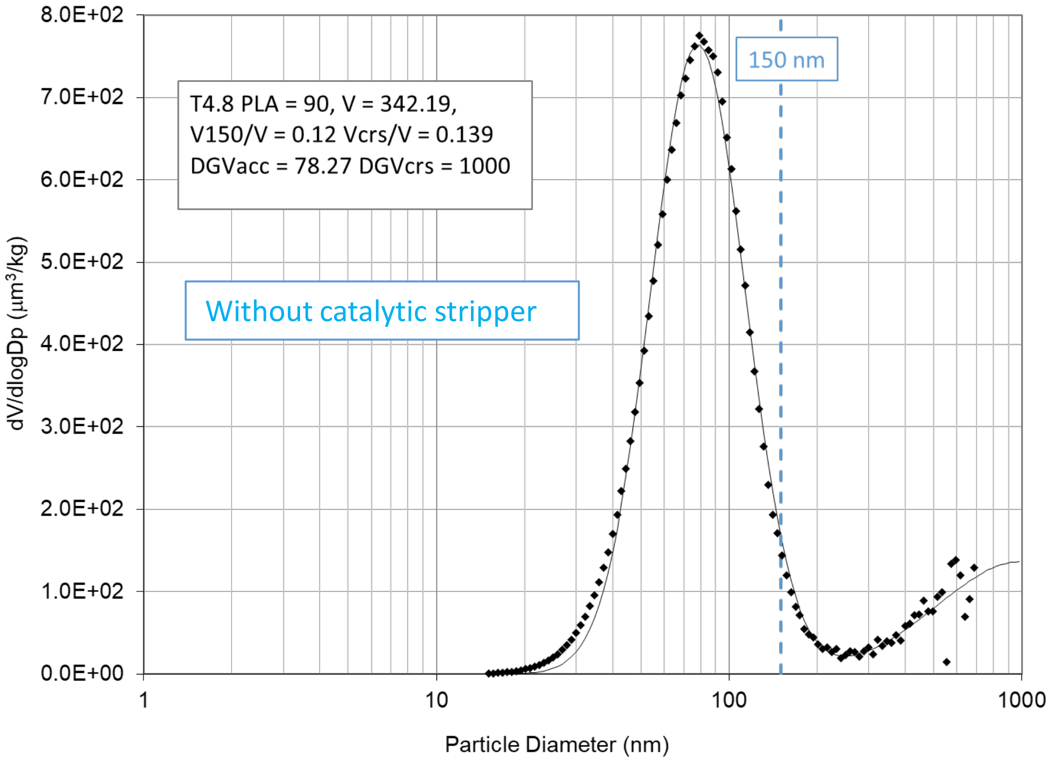
J-85 all fuels, V_{2nd}/V decreases with load and total particle volume but increase with camelina content – little impact of Catalytic Stripper (CS)





Bimodal lognormal fits to SMPS PSDs for two essentially matched J-85 Jet-A operating conditions with and without catalytic stripper (CS).



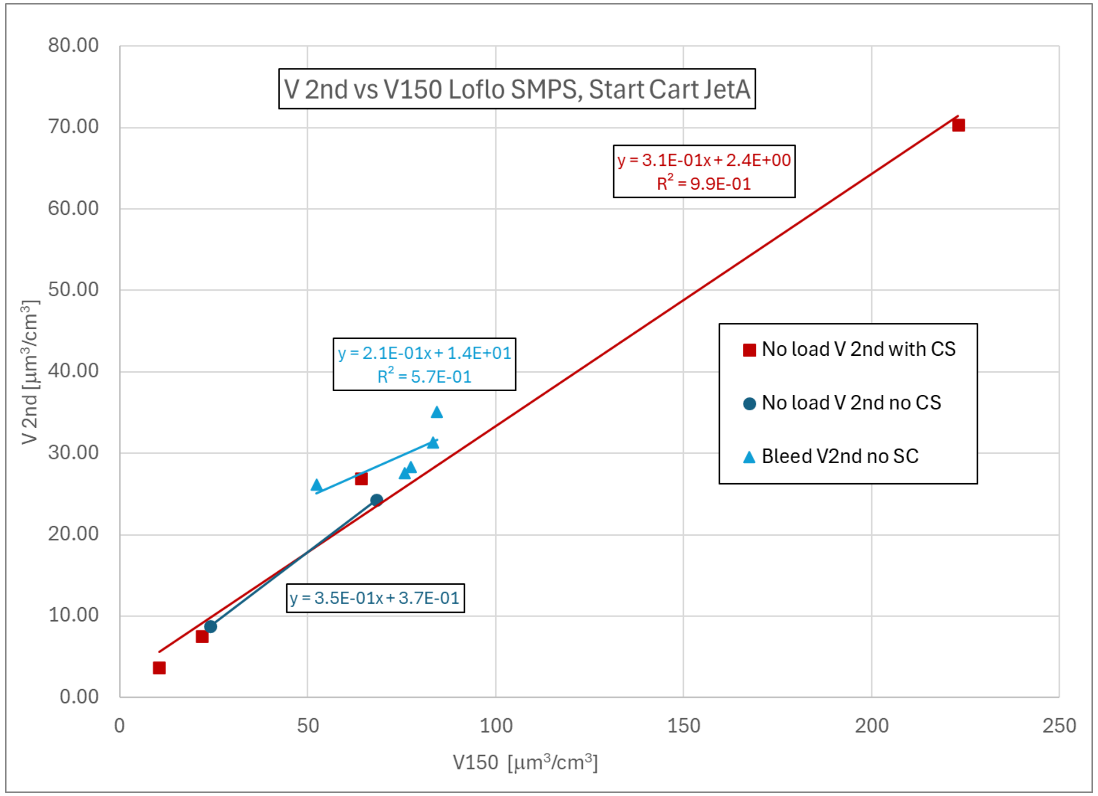


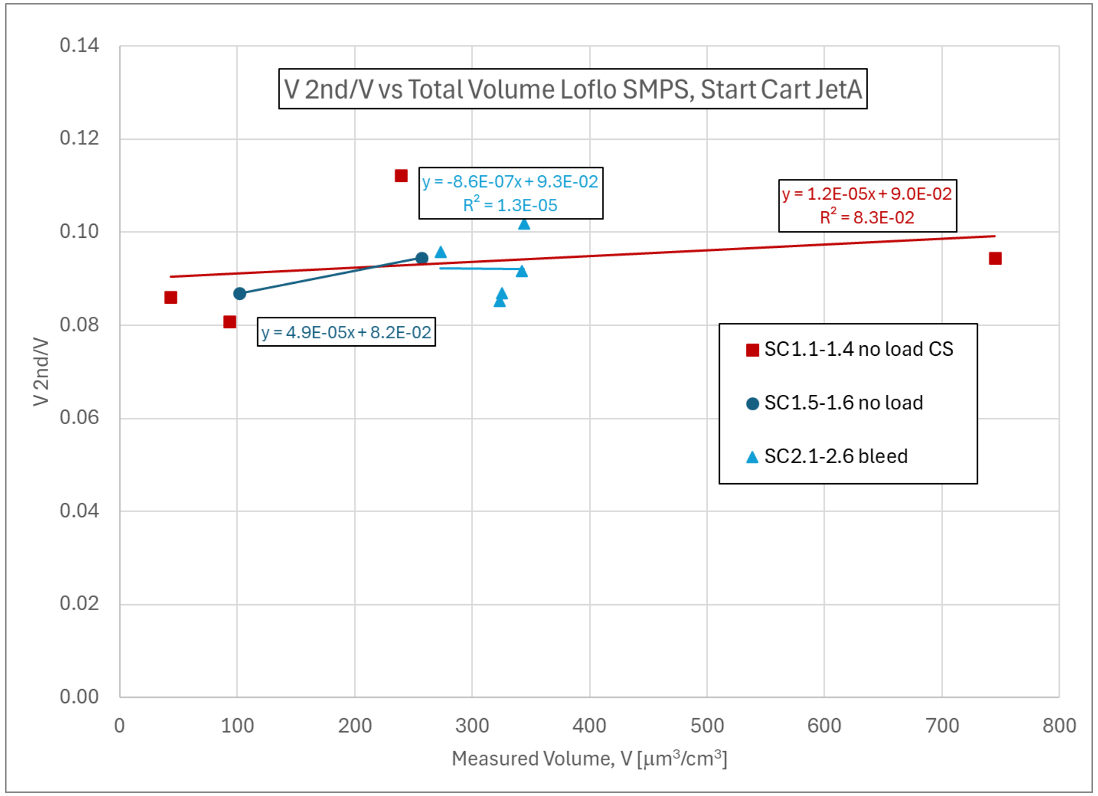
Fitted 2nd mode not removed by CS suggesting particles nonvolatile

Additional tests not presented here

- Benchtop CS experiments with miniCAST soot vs J-85
- Thermograms measured by OC/EC instrument
- All indicate nearly non-volatile nature of the 2nd mode

Start Cart Particles are Quite Different from those of J-85





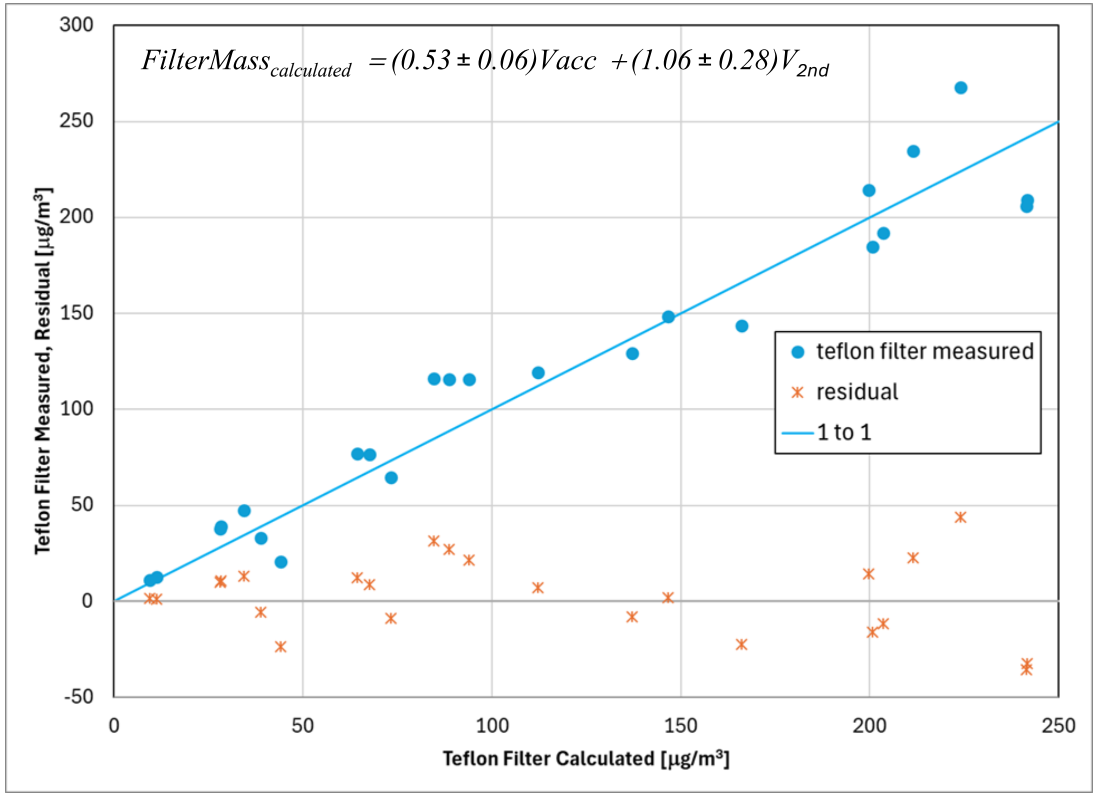
Slope of V2nd vs V150 is smaller than J-85

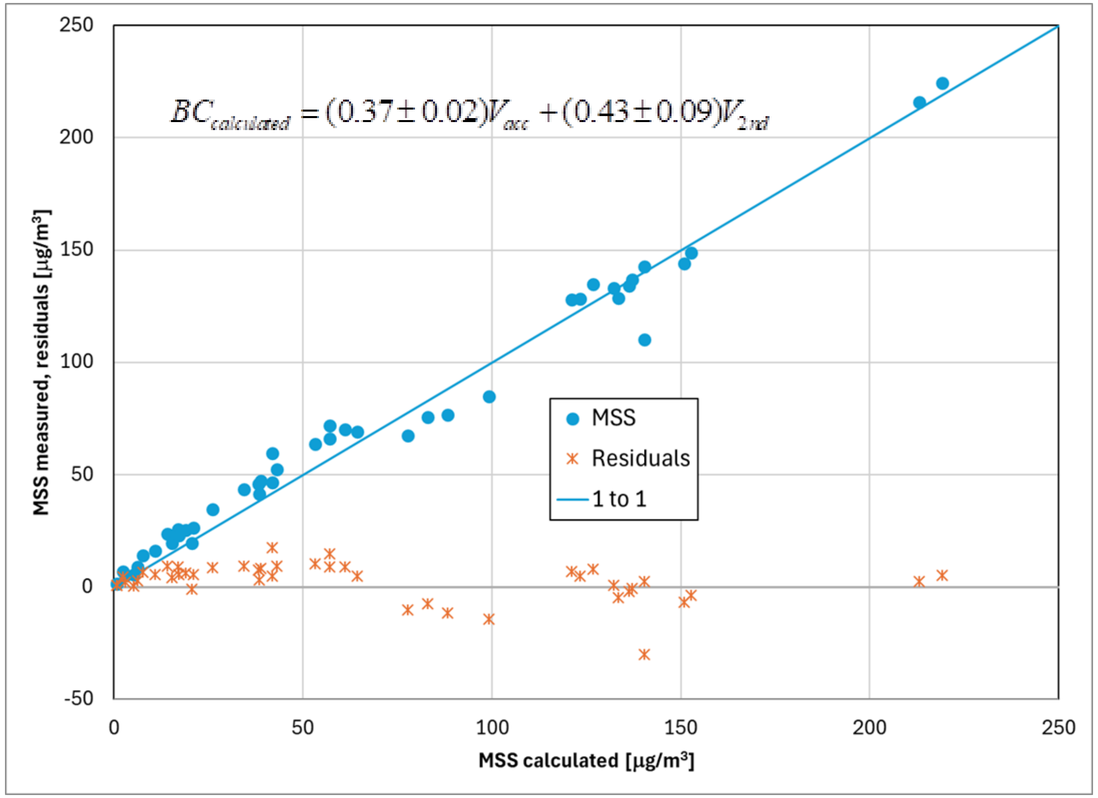
V2nd nearly independent of total volume

Properties of fitted V2nd modes are different from those of the accumulation mode

- 2-D linear regressions of specific properties against the fitted volume in the accumulation mode (V_{acc}) and the fitted volume in the 2nd mode (V_{2nd}) were performed to examine property differences
  - Gravimetric Teflon filter mass
  - MSS Black Carbon mass
  - LII Black Carbon mass
  - Aerodyne CAPS PM_{SSA} Black Carbon mass
- Results suggest that the physical properties of the accumulation mode and the second mode are different.

2-dimensional fits of Teflon Filter Mass and MSS BC to V_{acc} and $V2^{nd}$ suggest properties of accumulation and 2^{nd} modes are different





Physical and chemical properties measured with a miniSPLAT

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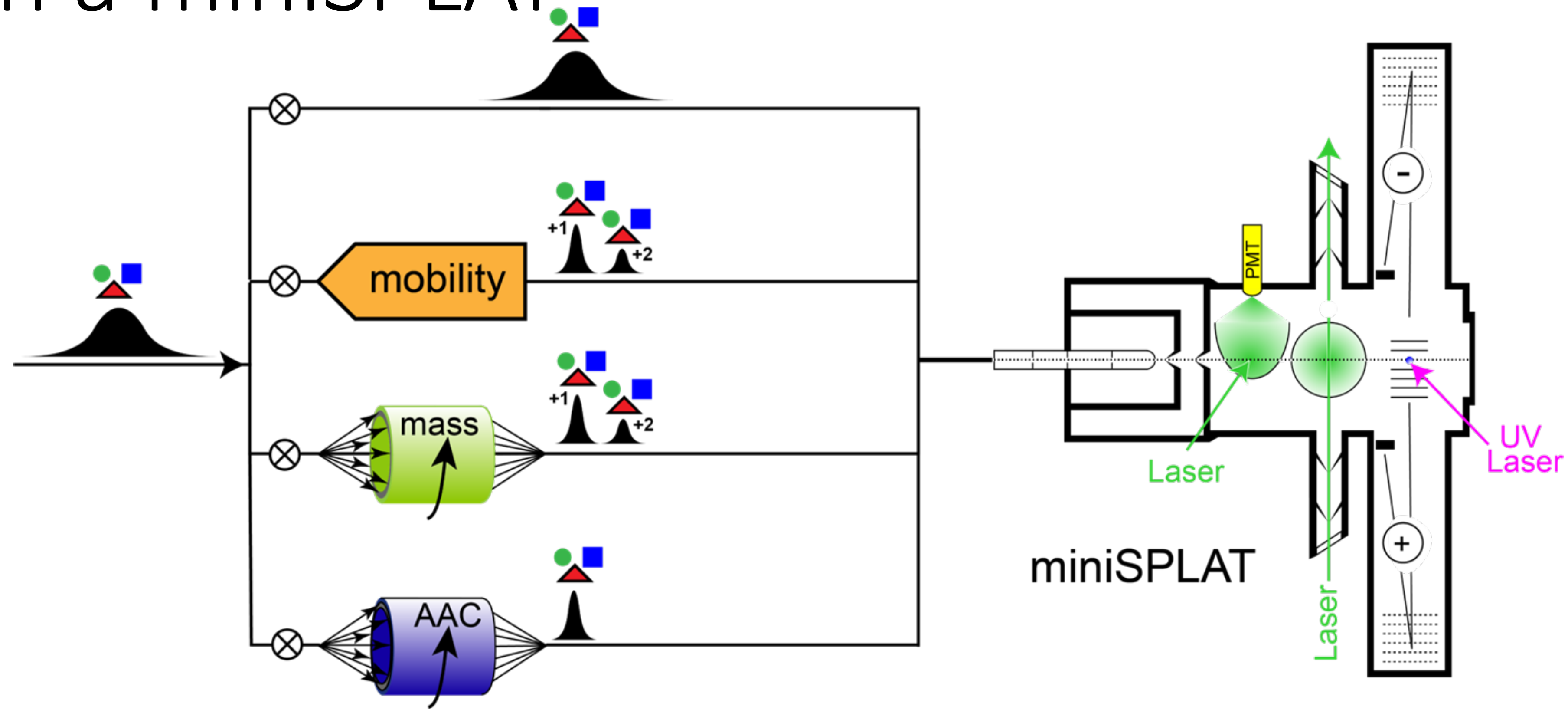
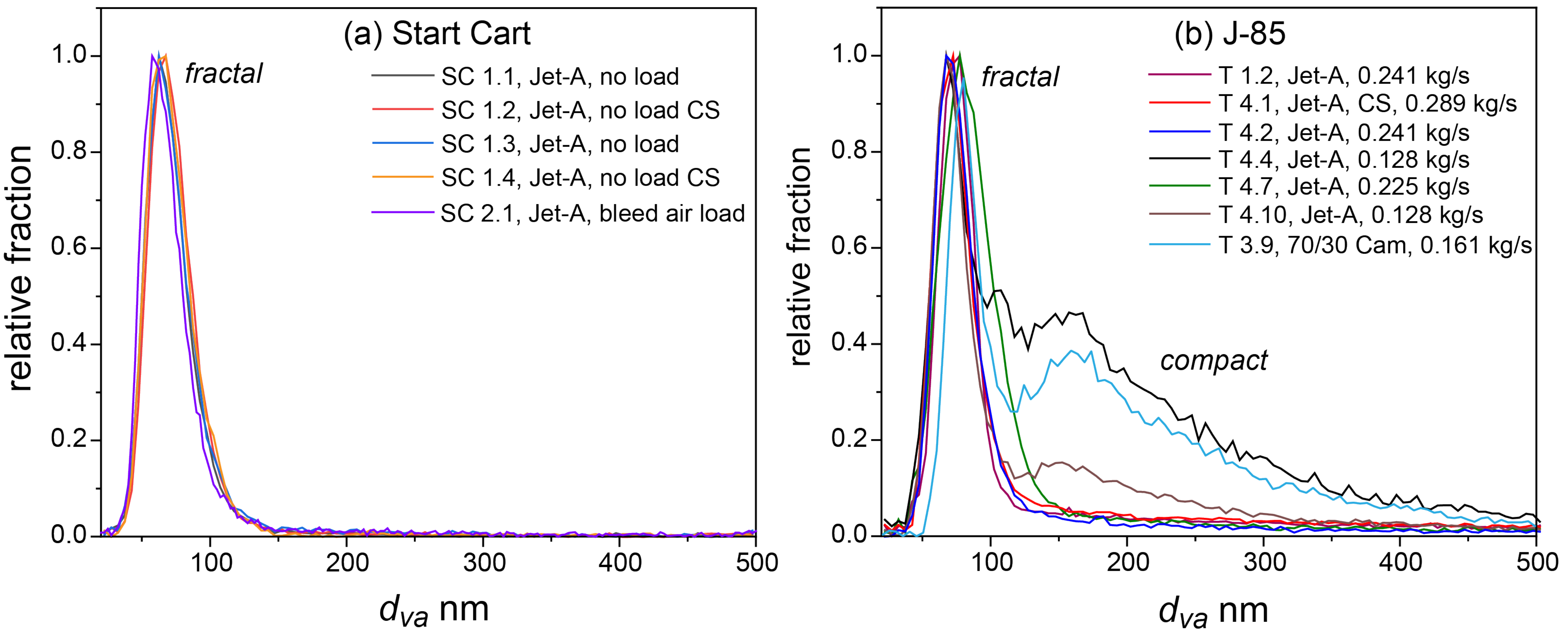


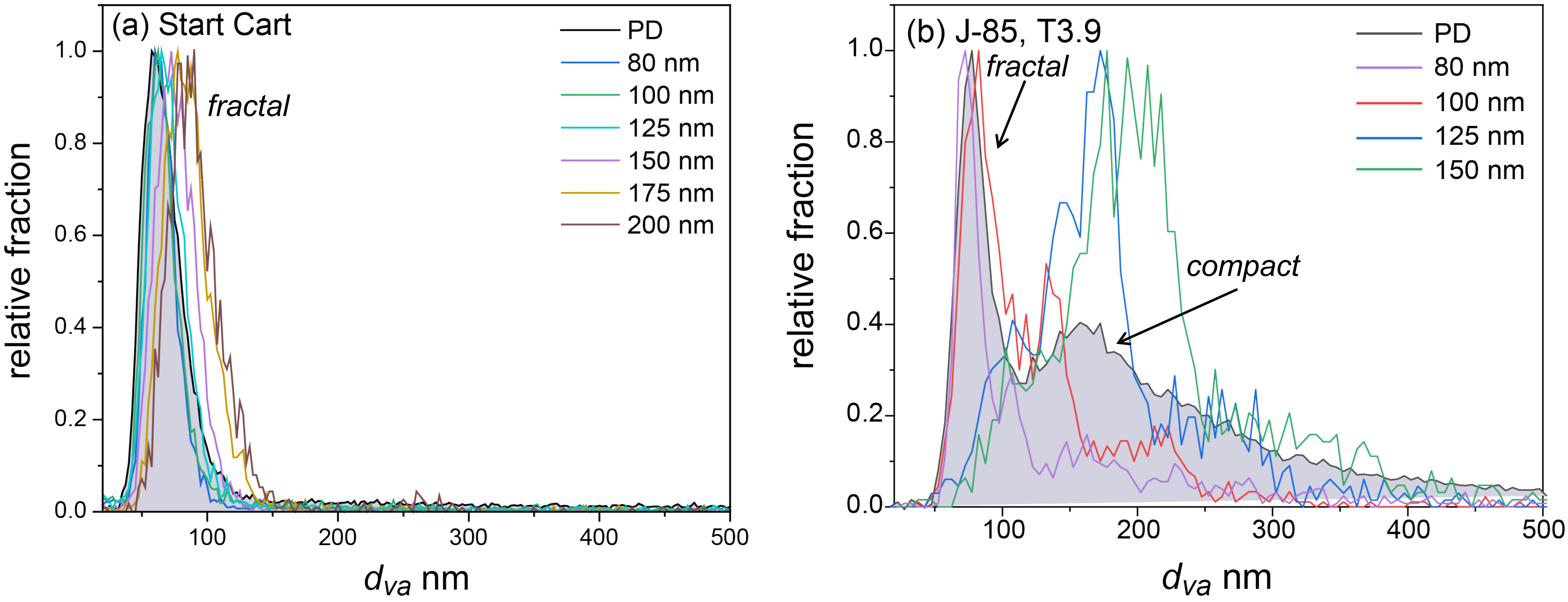
miniSPLAT measures the vacuum aerodynamic diameter (d_{va}) and mass spectra (*MS*) of all individual particles and particles with narrow distributions of properties (mobility diameter, mass, or aerodynamic diameter)

Representative miniSPLAT-measured d_{va} size distributions (a) Start Cart and (b) J-85



Nearly all J-85 d_{va} distributions have a 2nd mode present, which is not the case for Start Cart.

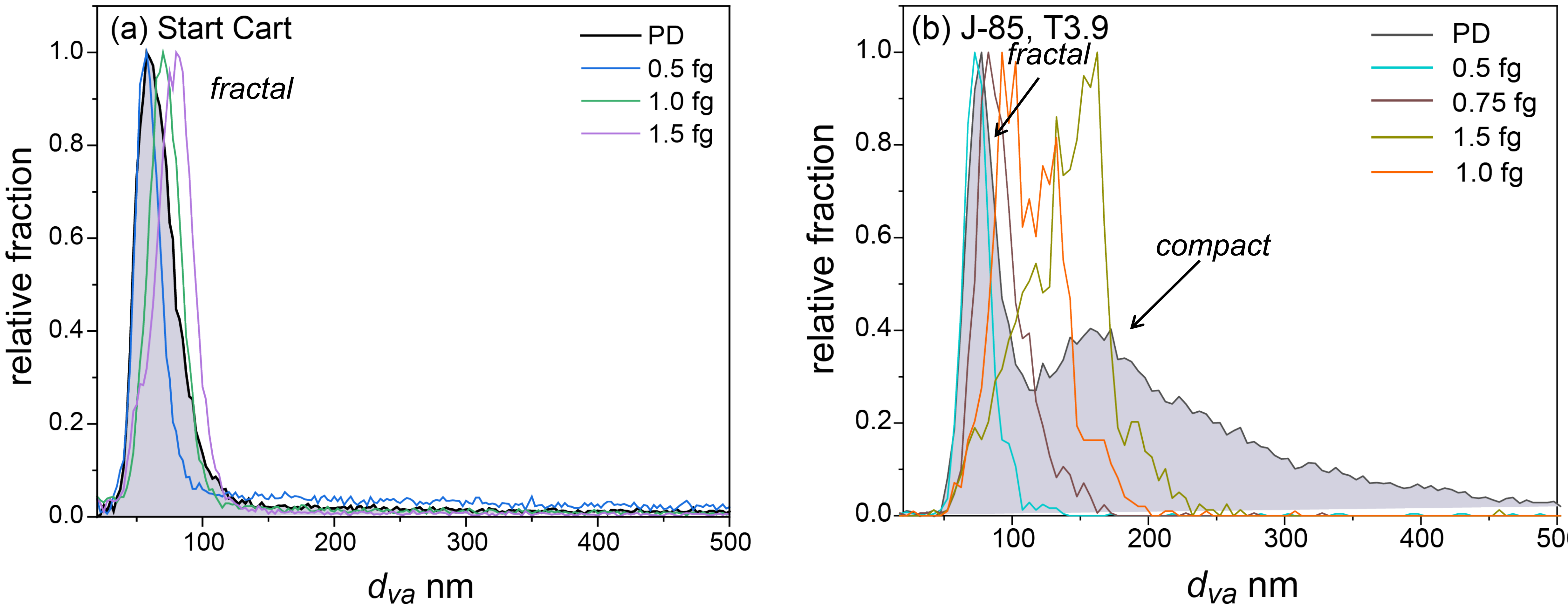
miniSPLAT-measured d_{va} size distributions for size (d_m)-selected particles (a) Start Cart and (b) J-85



J-85 Particles with larger d_m contribute mainly to the 2nd mode of the d_{va} distribution.

For Start Cart, particle d_{va} sizes are nearly independent of particle *dm*, indicating their fractal morphology.

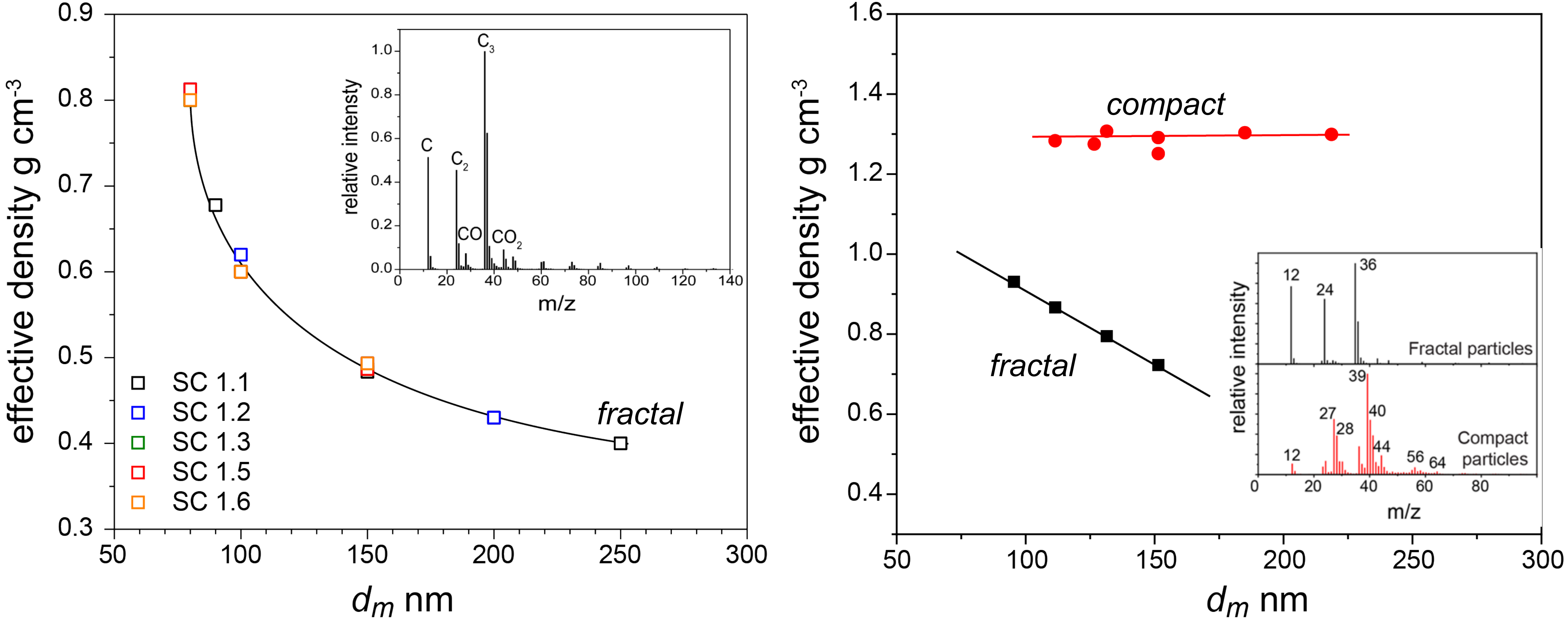
miniSPLAT-measured d_{va} size distributions for mass-selected particles (a) Start cart and (b) J-85



J-85 Particles with higher masses contribute largely to the 2nd mode of the d_{va} distribution.

For Start Cart, particle d_{va} sizes are nearly independent of particle mass, indicating their fractal morphology.

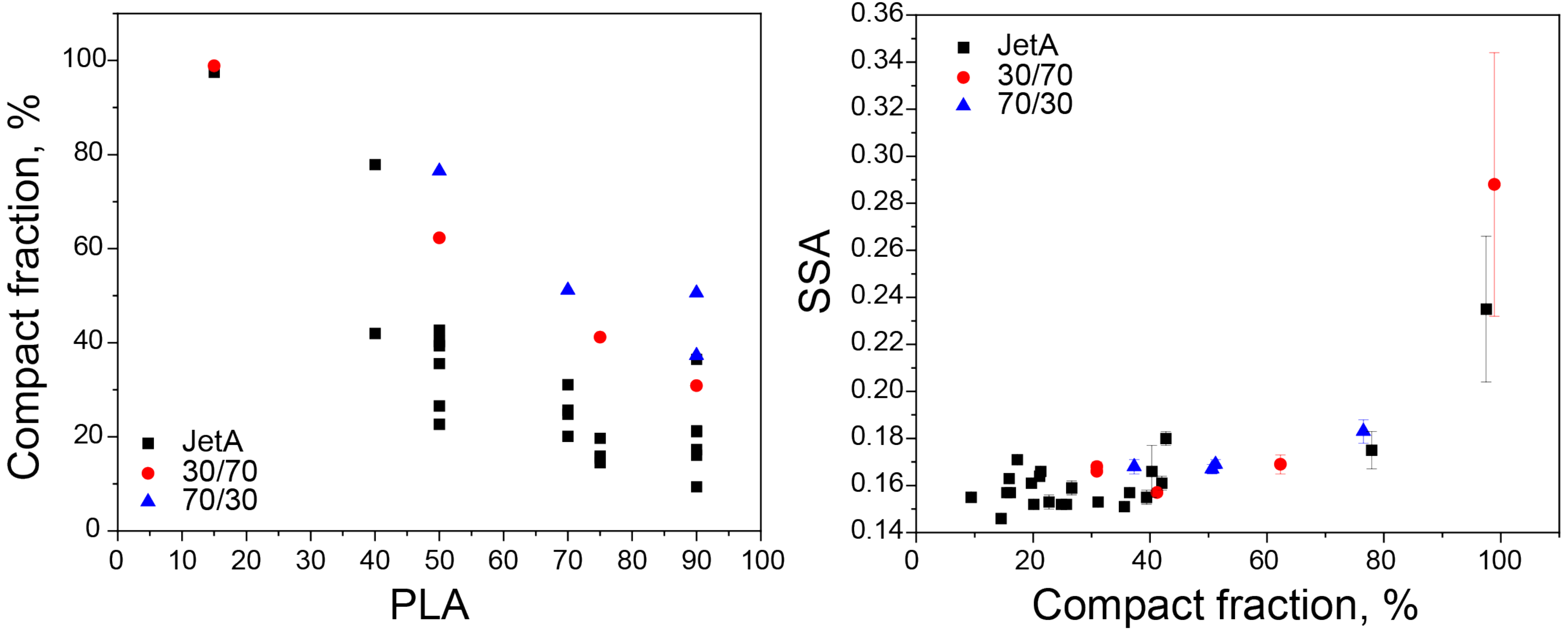
miniSPLAT-measured size-dependent particle effective density (a) Start cart and (b) J-85 (T3.9)



Start Cart particles are dominated by EC and have effective densities that decrease with particle d_m

J-85 particles represent a mixture of fractal soot particles and compact particles, containing high OC and ash

Fraction of compact particles increases with decreasing PLA for all fuels

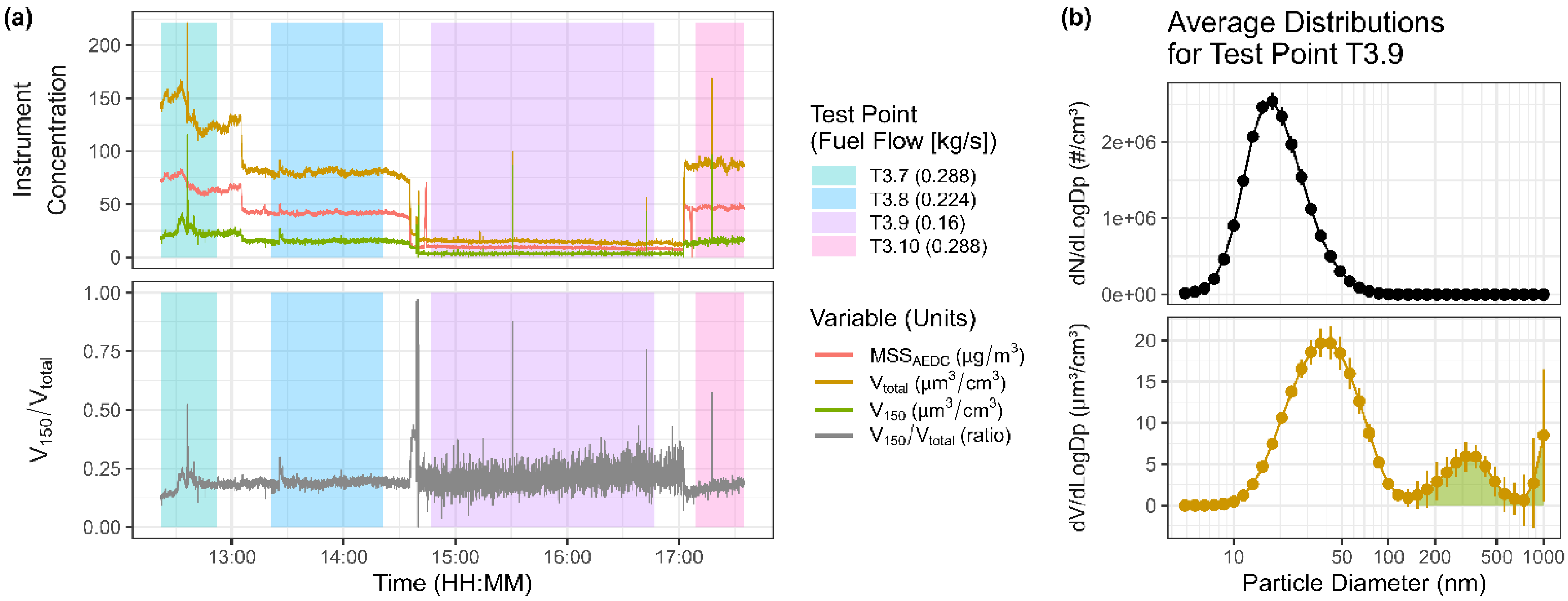


Compact, OC-dominated particles with larger *d*va are less absorbing, providing an explanation for the higher single-scattering albedo (SSA) values measured by CAPS.

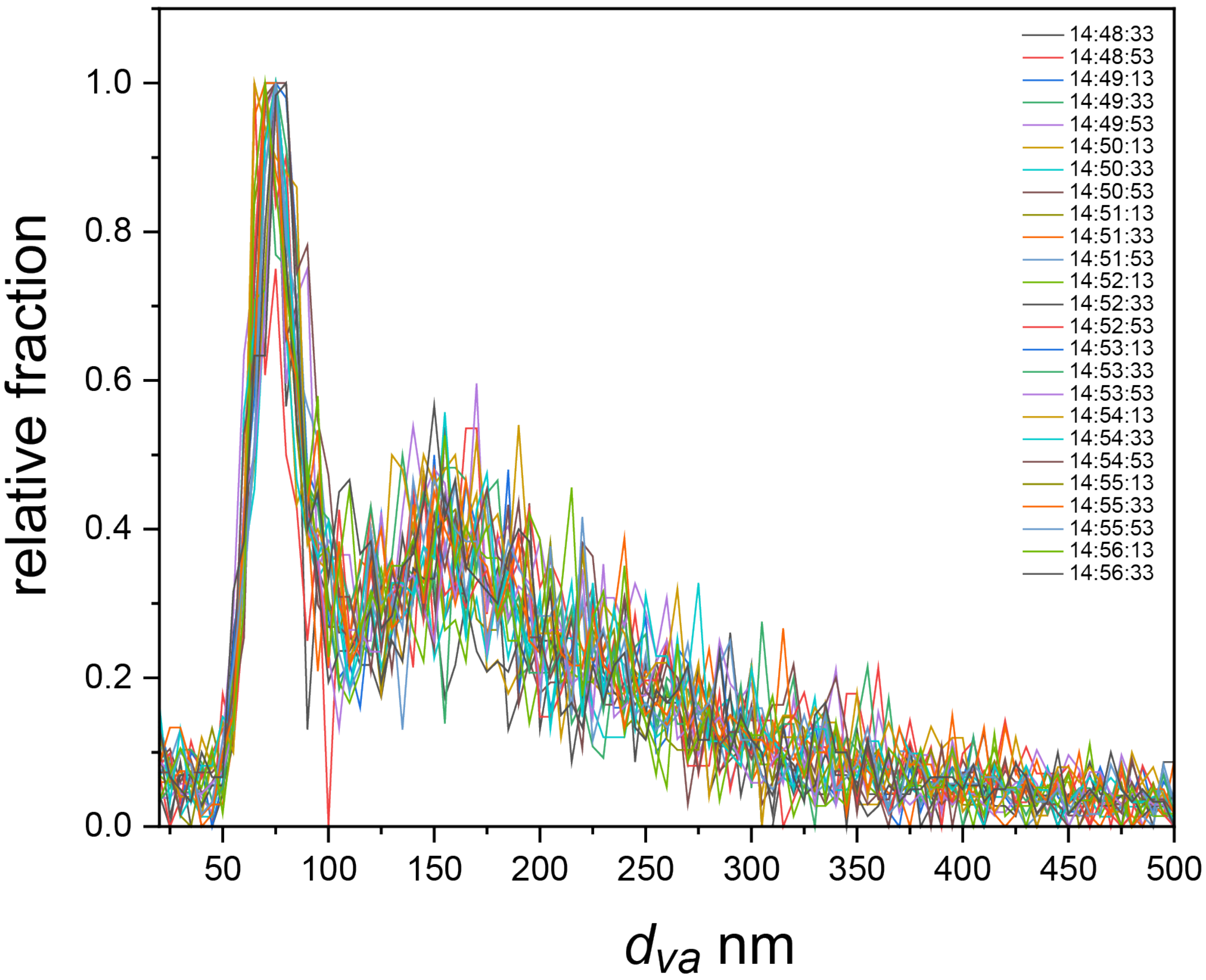
Are these particles real or sampling artifact?

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

(a) MSS mass and DMS500 total particle volume, Volume above 150nm and Volume fraction above 150 nm over four tests on August 14, 2018. Shaded regions mark each test, and the legend gives average fuel flow. (b) Average number- and volume-weighted DMS500 PSDs for test T3.9; the green region shows volume above 150 nm, and error bars indicate ±1 SD.



miniSPLAT-measured d_{va} size distributions for T3.9 J-85 70% Camelina



Measured particle d_{va} size distributions, plotted at 20 seconds resolution, exhibit two highly reproducible and persistent modes that are consistent with **fractal** and **compact** particle populations.

Conclusions - 1

- 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
- It was observed in four test programs (2014-2018) on same engine model using a variety of metrics including:
  - 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 - 2

- The accumulation and 2nd modes have different physical properties
  - Density
  - Optical black carbon instrument response
  - 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 with higher effective density and mass. Mass spectra were more complex with peaks associated with a higher fraction of organic carbon and ash (Ca, Zn compounds)
- ***We still don't understand how 2nd mode particles are formed***

Thank you for your attention, questions

Disclaimer

The views expressed in this presentation are those of the author[s] and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency.

The many participants in the VARIAnT program are listed in the titles below.

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