Particle Emissions from Aircraft Gas Turbines: A Coarse Size Mode from Low Emission Engines

David Kittelson
Department of Mechanical Engineering
University of Minnesota

Robert Giannelli, John Kinsey, and Jeff Stevens
United States Environmental Protection Agency

Robert Howard, Brandon Hoffman
U. S. Air Force, Arnold Engineering Development Complex (AEDC)

24th ETH-Conference on Combustion Generated Nanoparticles

June 22-24, 2021

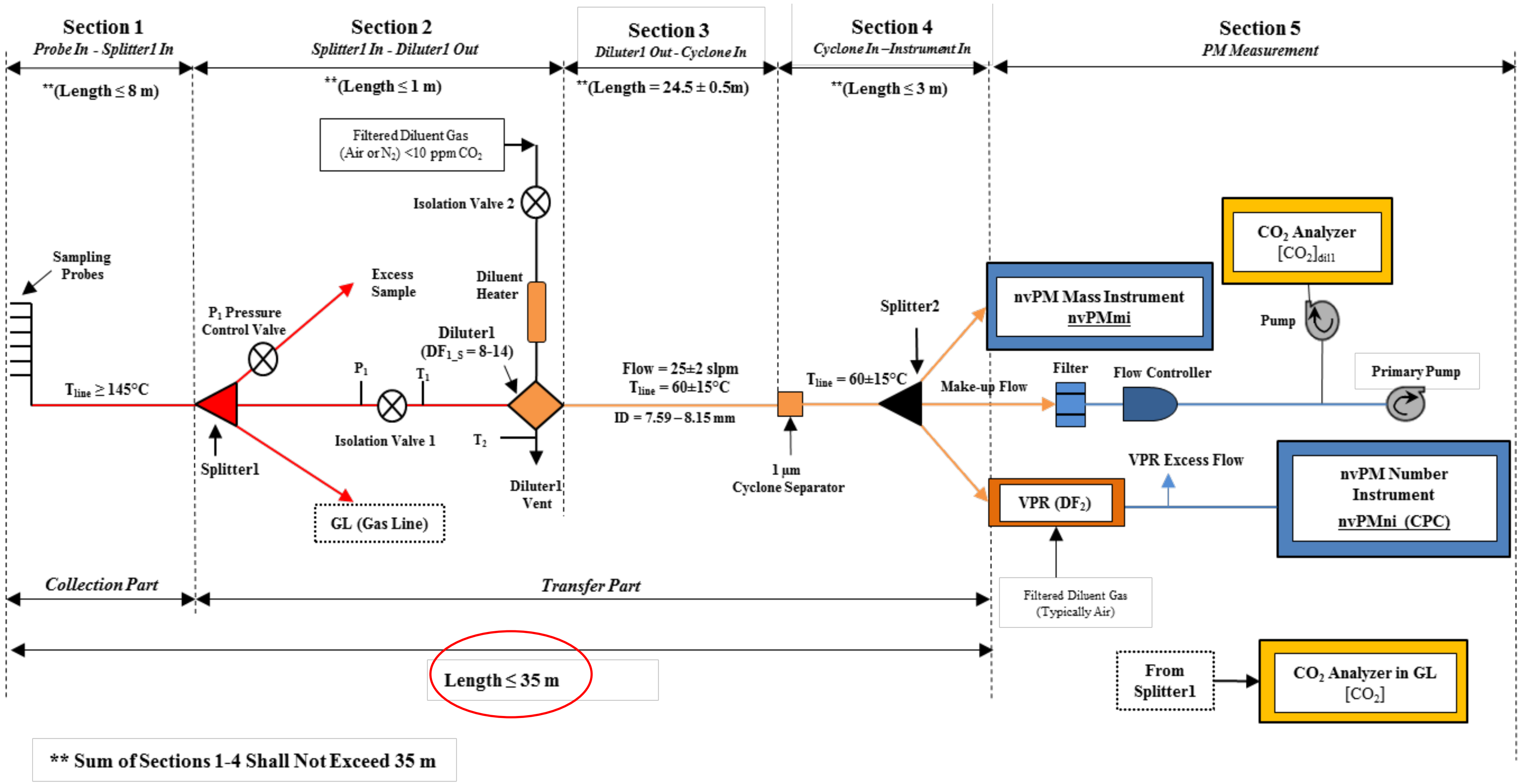
Online Conference

Introduction

- Aircraft gas turbine engine particles measured under typical laboratory test usually form a unimodal, essentially log-normal size distribution consisting mainly of carbonaceous soot aggregates in the accumulation mode
- Very long sampling lines are used for these measurements necessitating lead to significant size dependent particle losses
- A loss correction method has been developed
    - Assumes unimodal lognormal distribution at exhaust exit plane
    - Assumes density and sigma g are known
    - Assumes sampling system transfer functions are well known
    - Calculates GMD from measured N/m
- Recent measurements show that a coarse mode consisting mainly of particles larger than about 150 nm is present
- If there is significant mass in this mode, the current line loss correction won't work
- Is this mode real, what is it?

Long sampling lines necessitate a line loss correction based on mass and number measurements

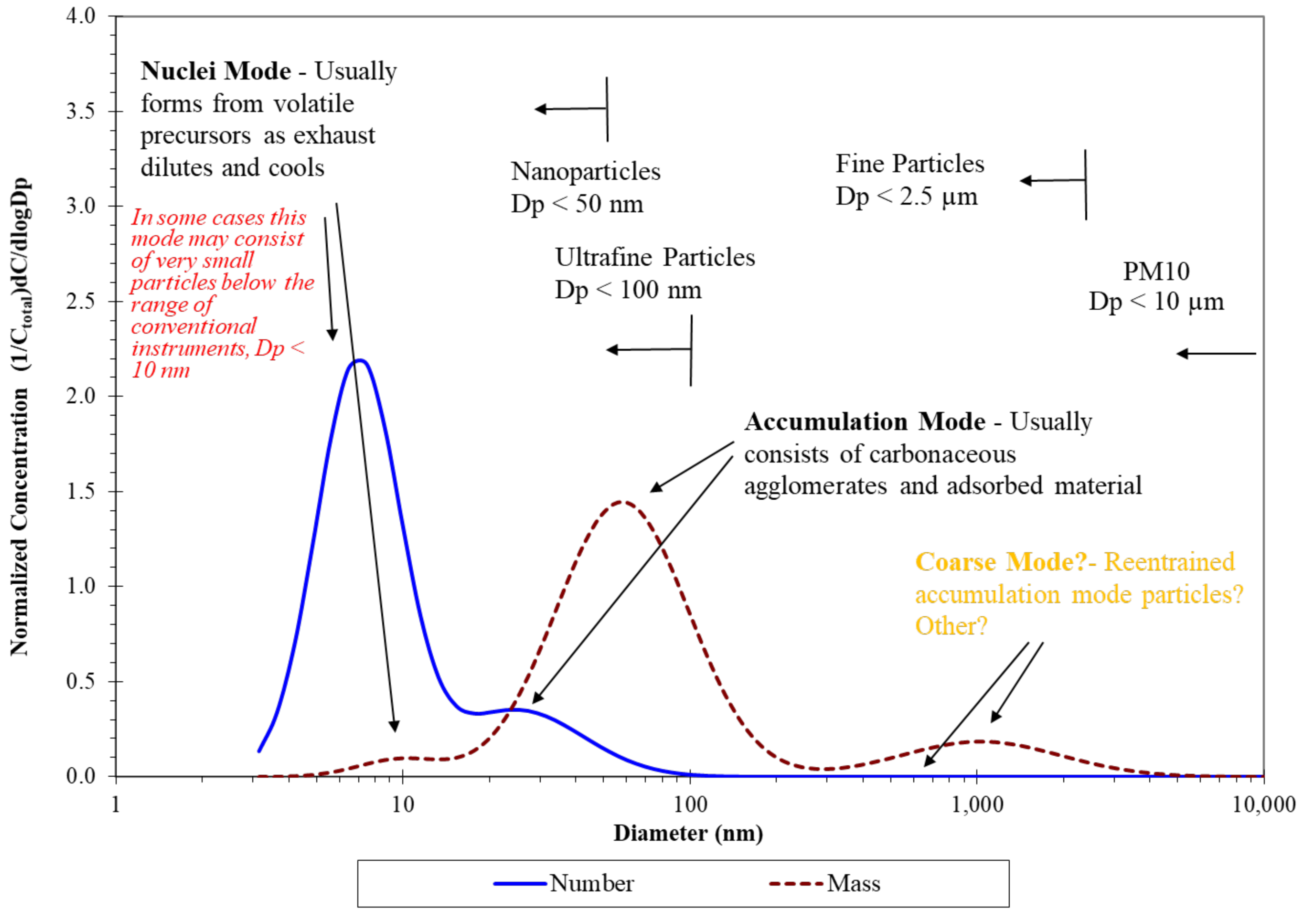
Recommended aircraft sampling line configuration (SAE International Aerospace Information Report 6241)



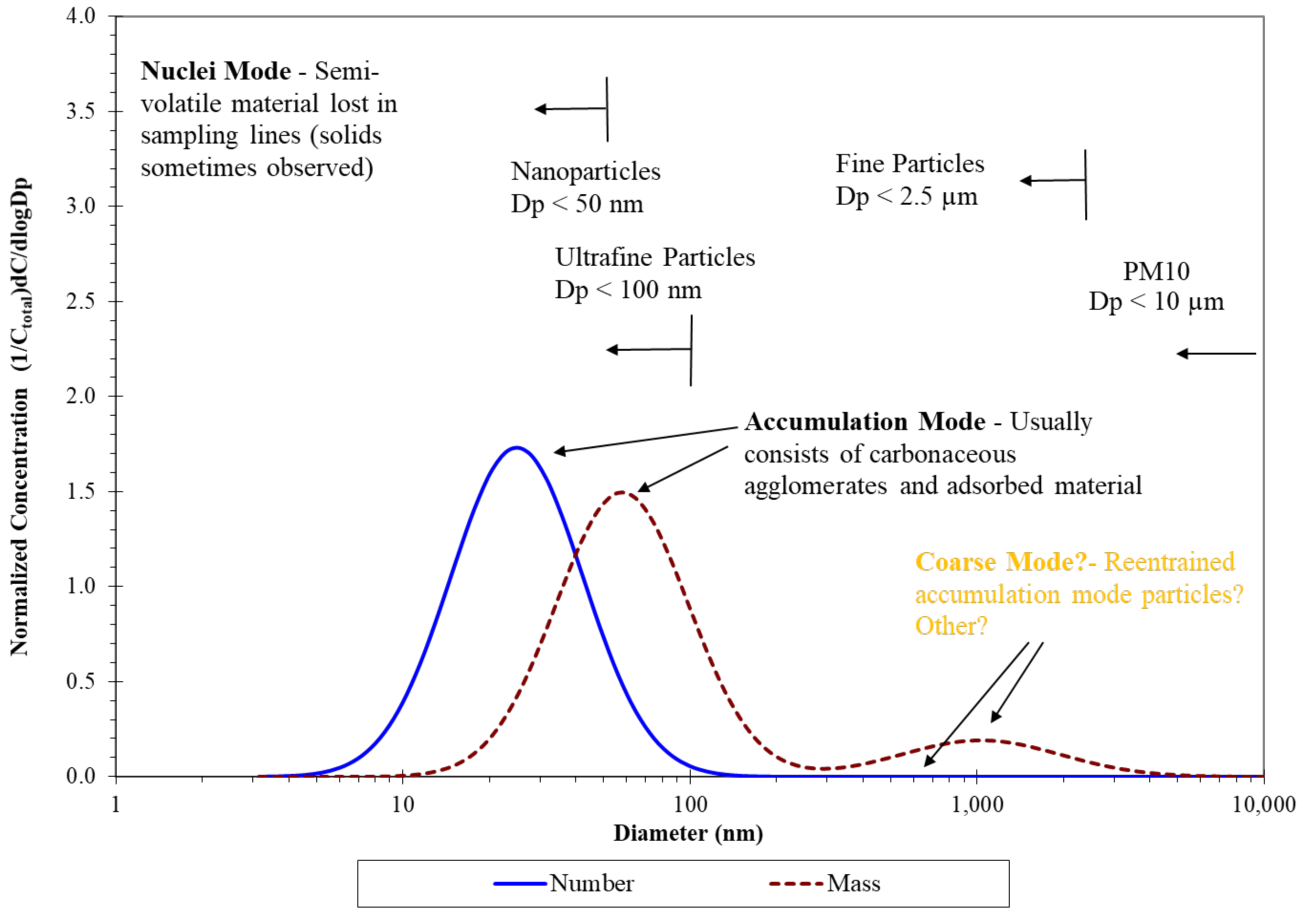
Measurement of non-volatile particles for aircraft gas turbine engine - coarse mode?

- Part of a long term USEPA study of issues associated with measurement of non-volatile mass and number from commercial aircraft gas turbine engines
- Measurements made at U. S. Air Force, Arnold Engineering Development Complex (AEDC)
- Engines tested
  - General Electric J-85 turbojet
  - Gas turbine aircraft auxiliary power unit (start cart)
- Sampling system similar to regulatory system
- Fuels – Jet A, 30% and 70% blends of Camelina (SAF) in Jet A

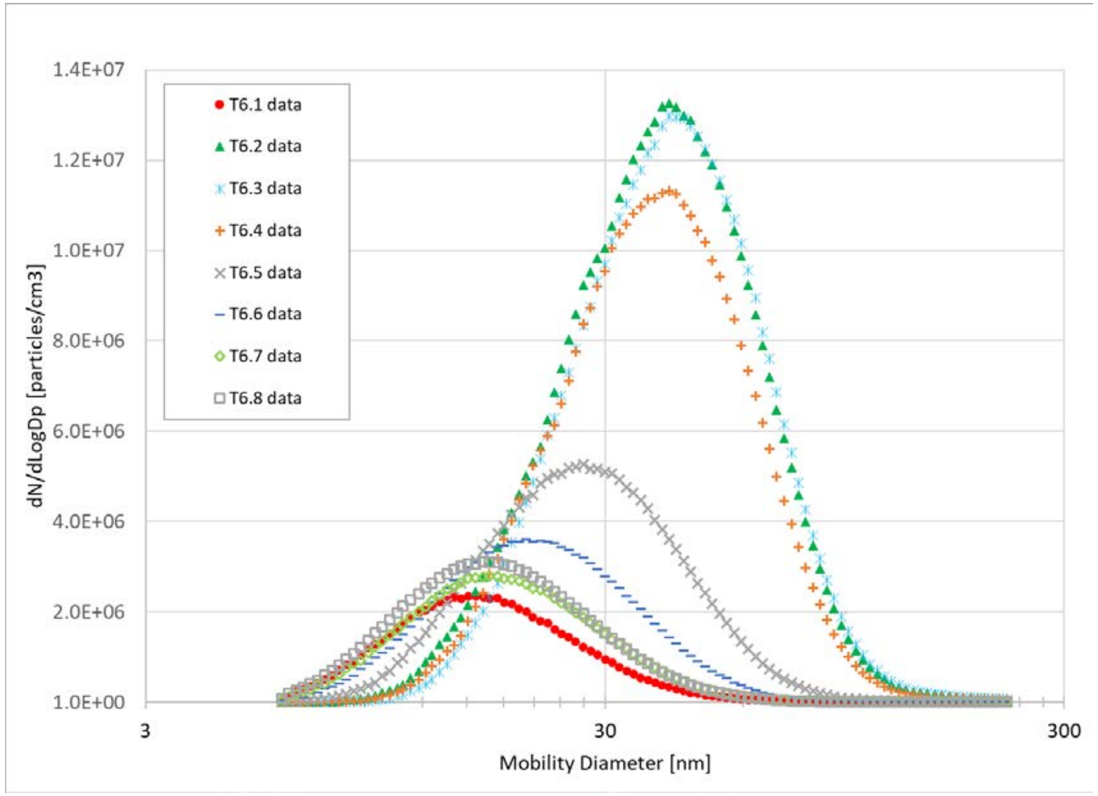
Gas turbine size distribution, very small particles, e.g., GMD accumulation mode ~ 25 nm.
Nucleation mode forms in atmosphere

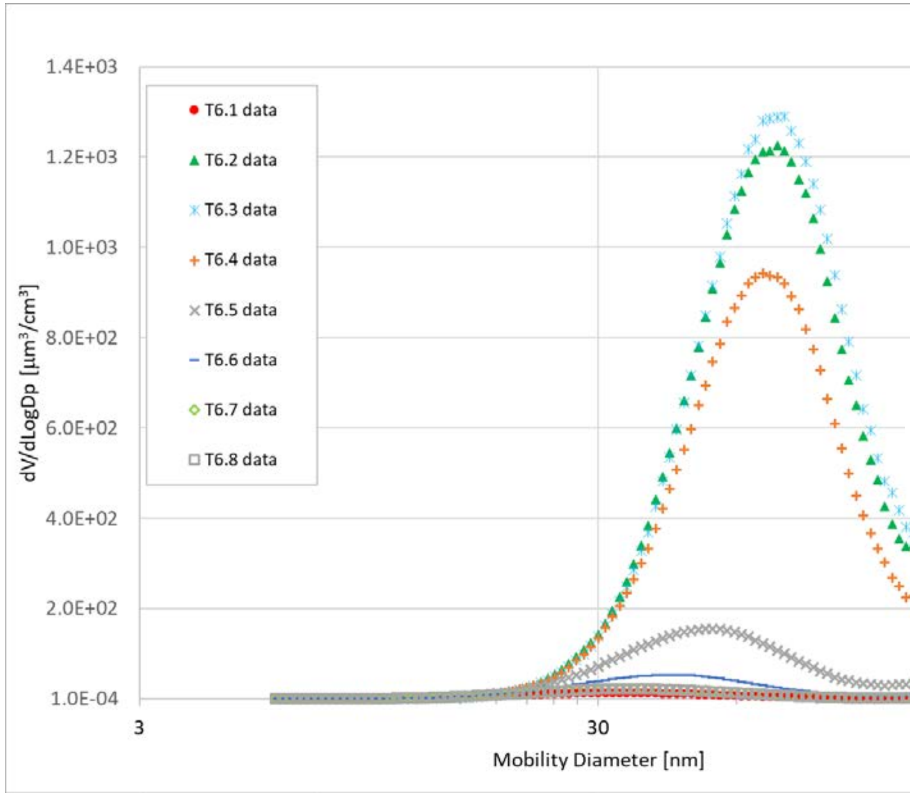


Gas turbine size distribution with certification sampling system, long lines, CS remove semi-volatile nucleation mode
Is there coarse mode?



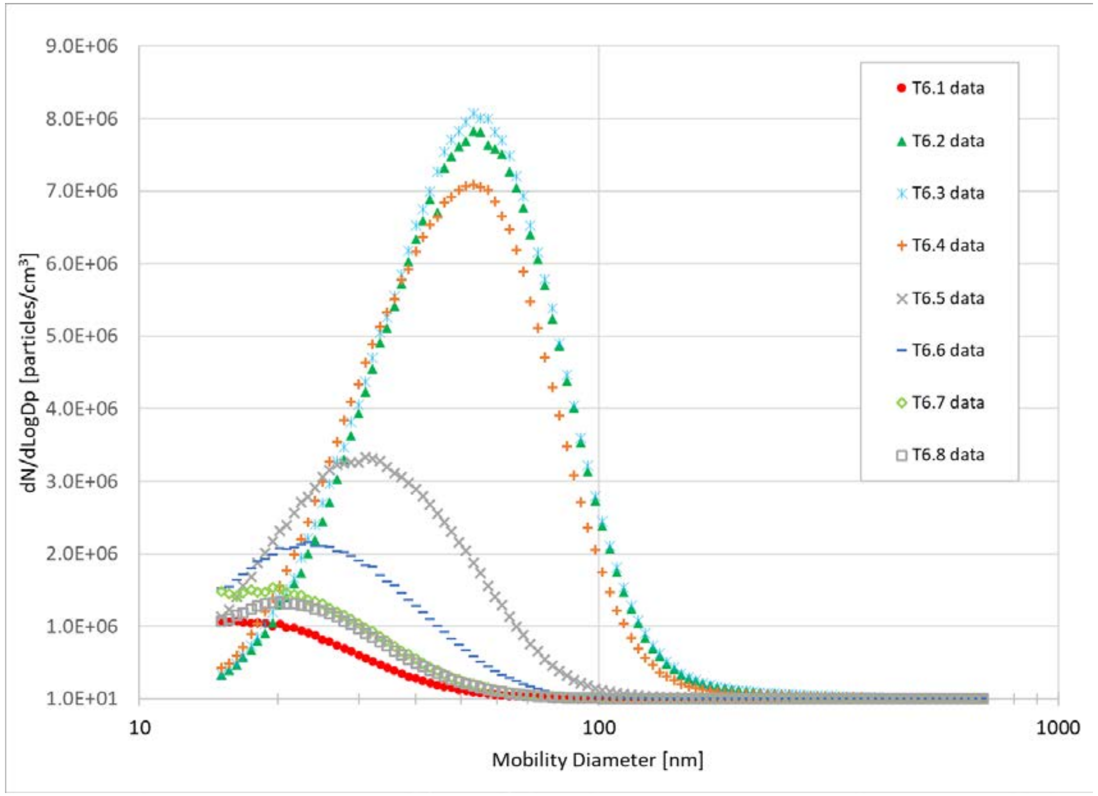
Number and volume size distributions, J-85 engine, Jet A fuel, SMPS (6 – 225 nm scan) various loads GMD 17 – 41 nm

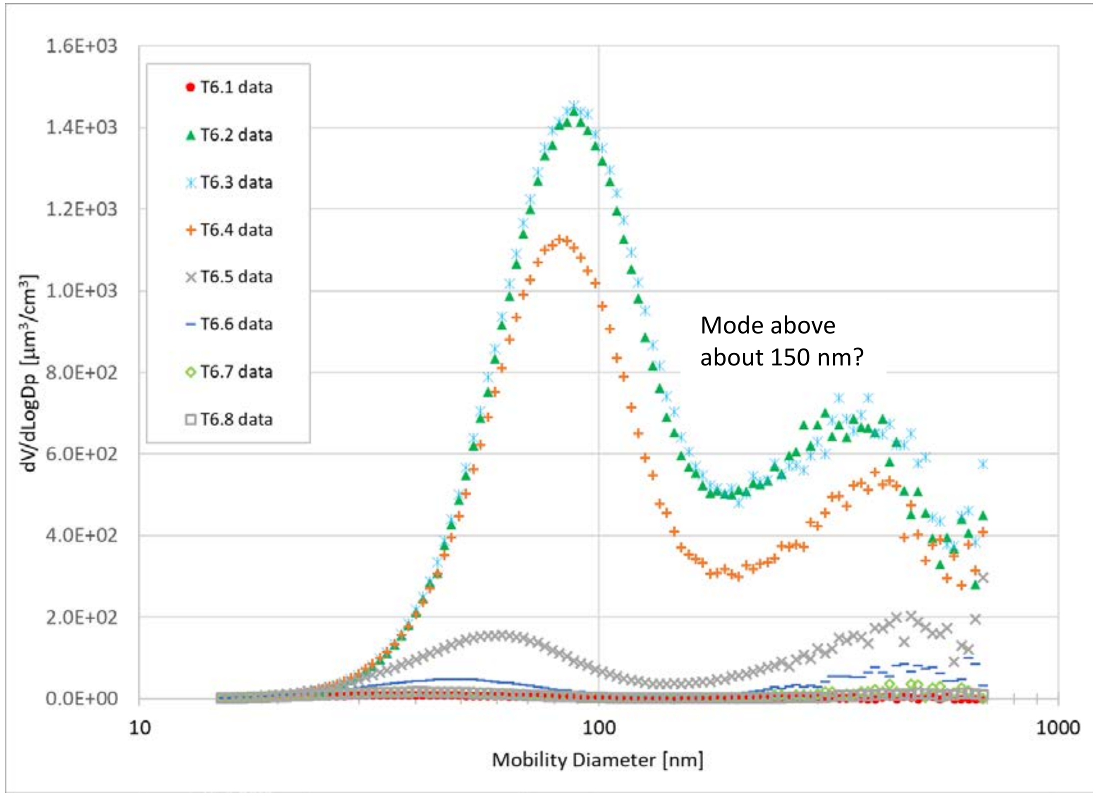




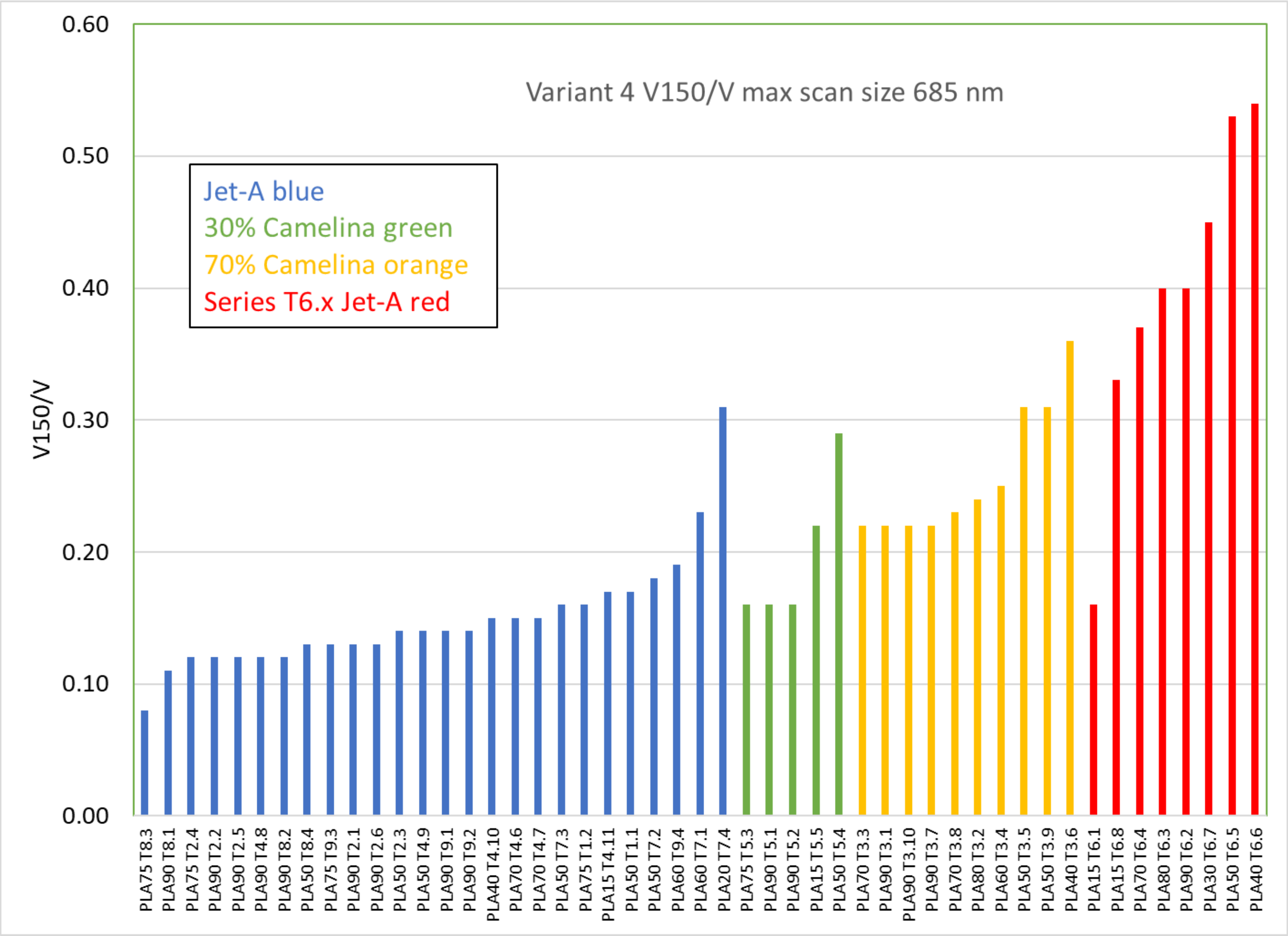
Mode above about 150 nm?

Number and volume size distributions, J-85 engine, Jet A fuel, SMPS (15 – 685 nm scan)



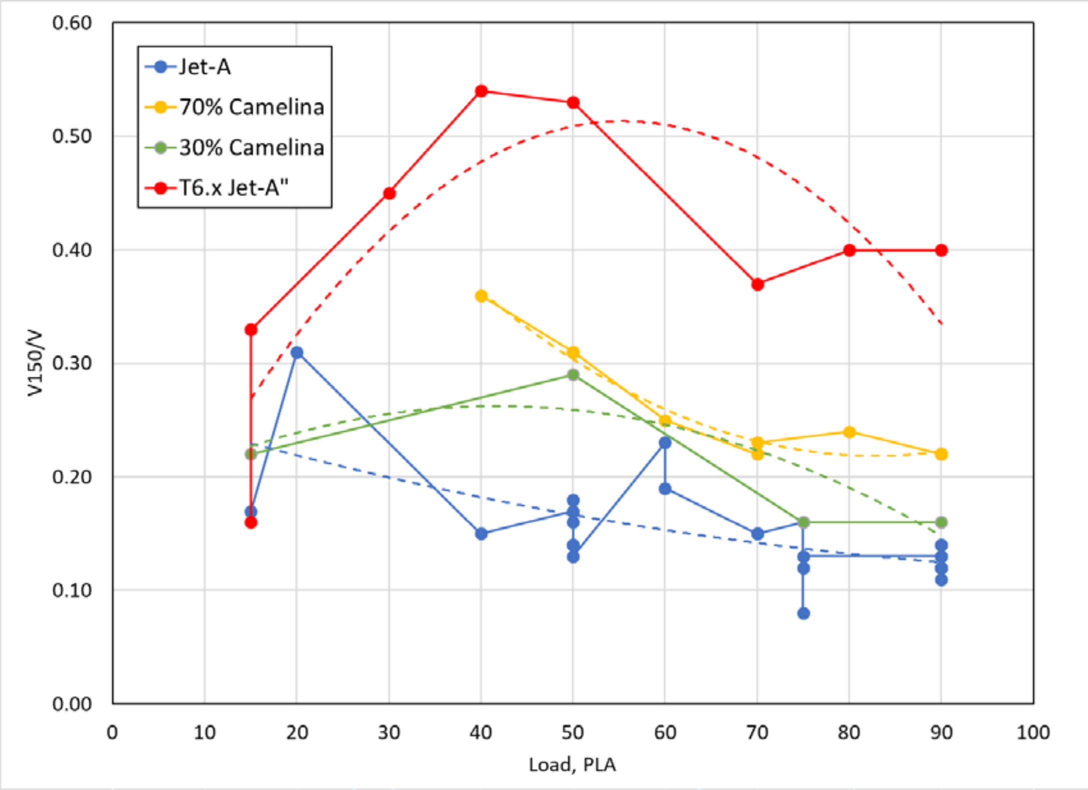


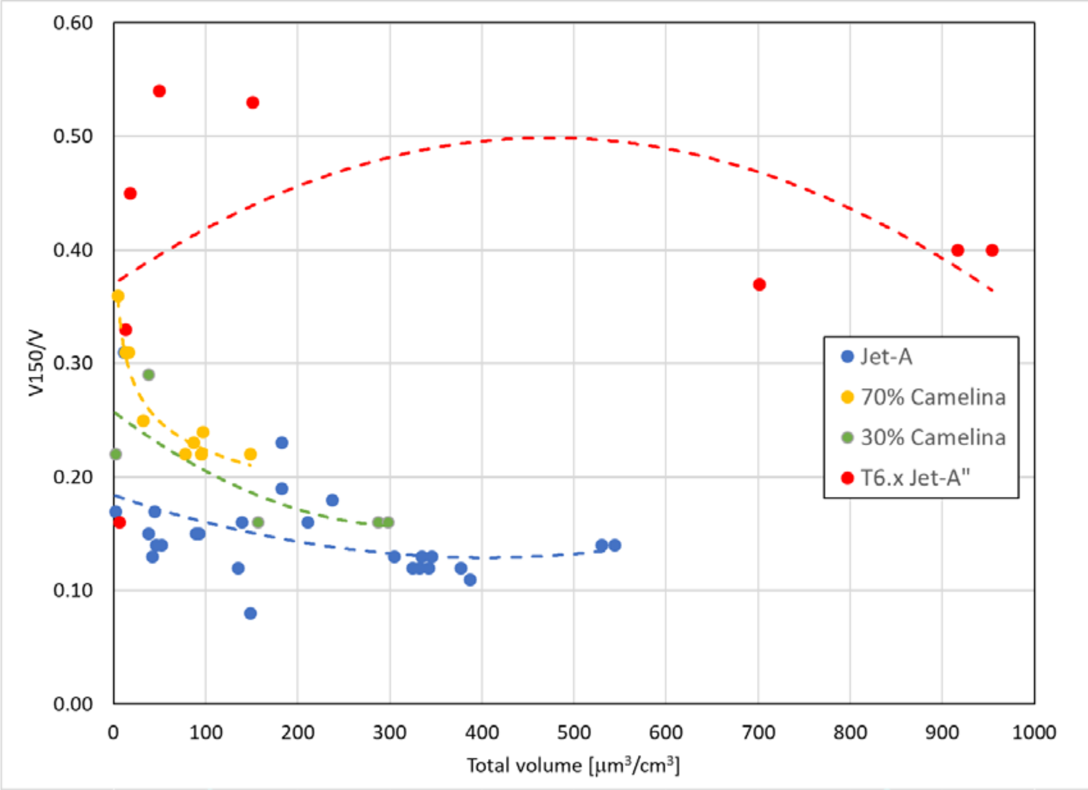
Coarse fraction, V150/V, by test condition



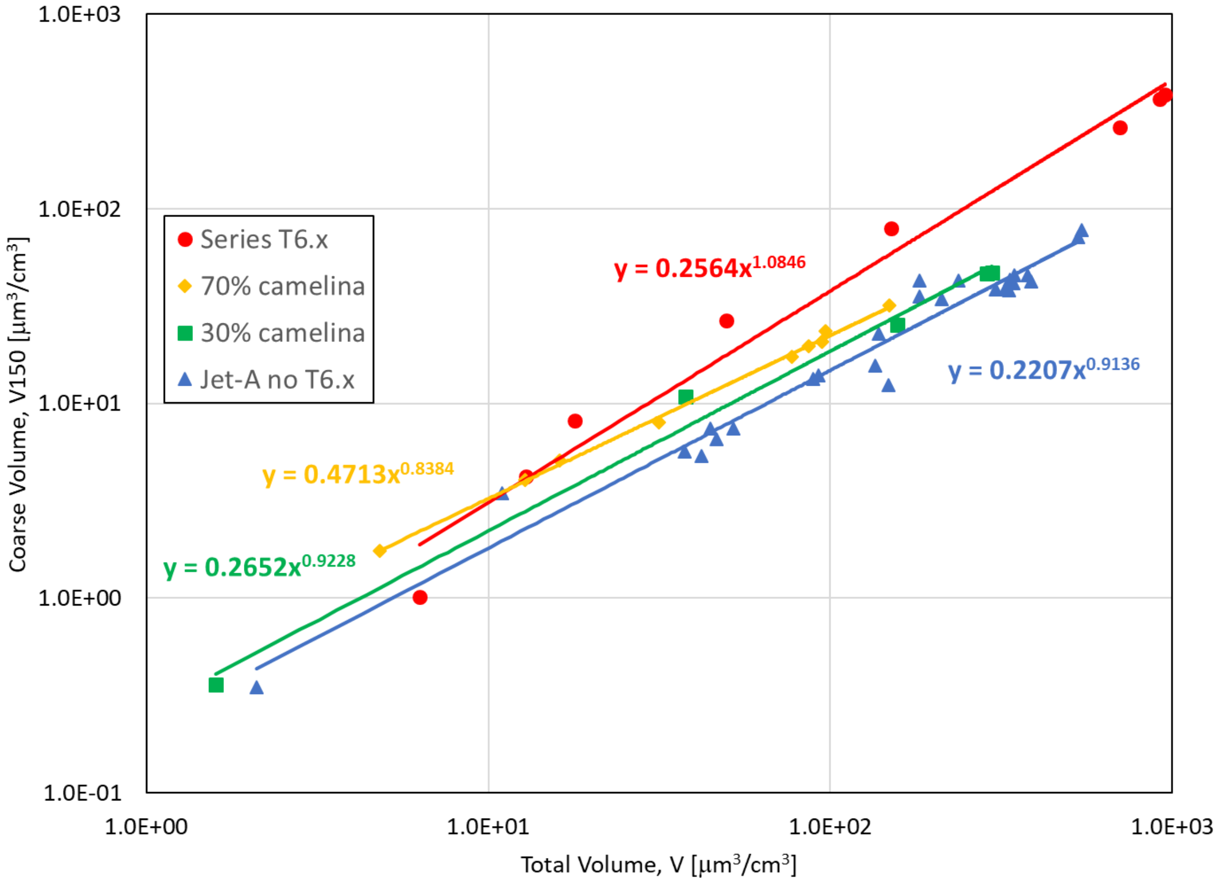
- PLA (power lever angle) is an indicator of thrust, PLA10 idle, PLA90 maximum
- T1.x to T9.x correspond to different test days
- In most cases coarse fraction increases with decreasing load
- Except for series T6, Camelina (SAF) blends gave the highest coarse fractions
- T6 test series gave unusually high V150/V ratios

Coarse fraction higher with SAF, decreases with load and total volume concentration, except T6

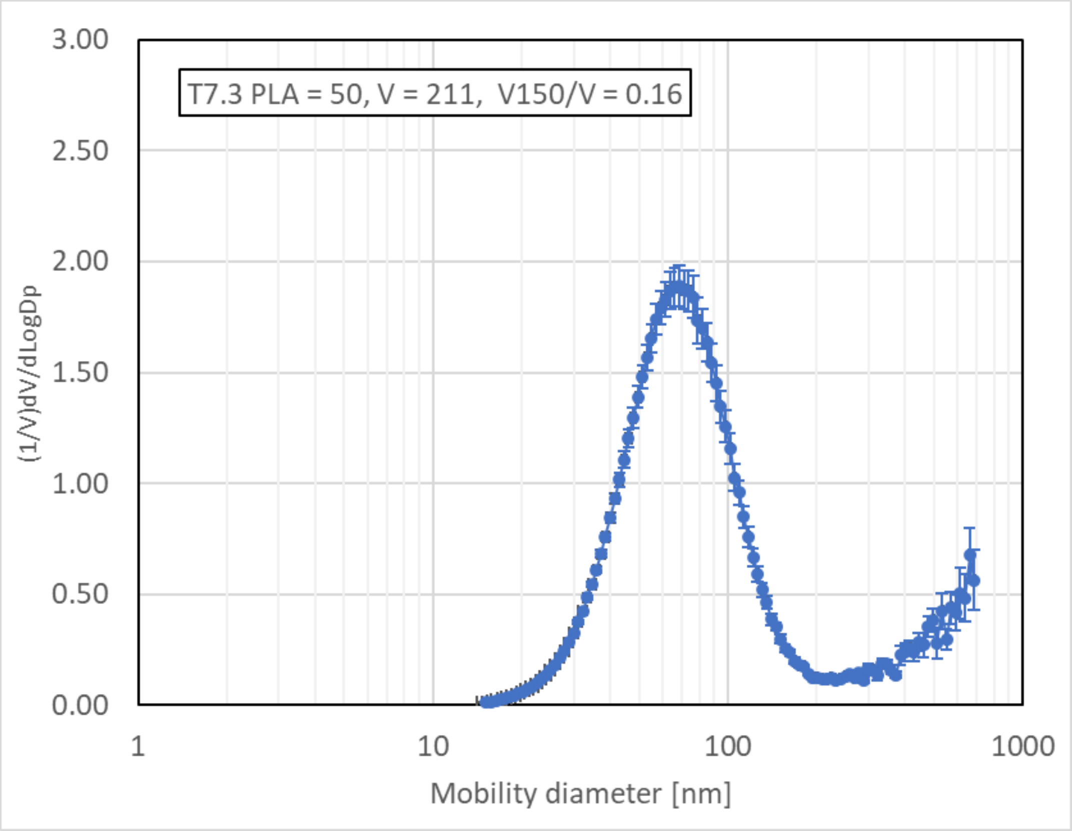


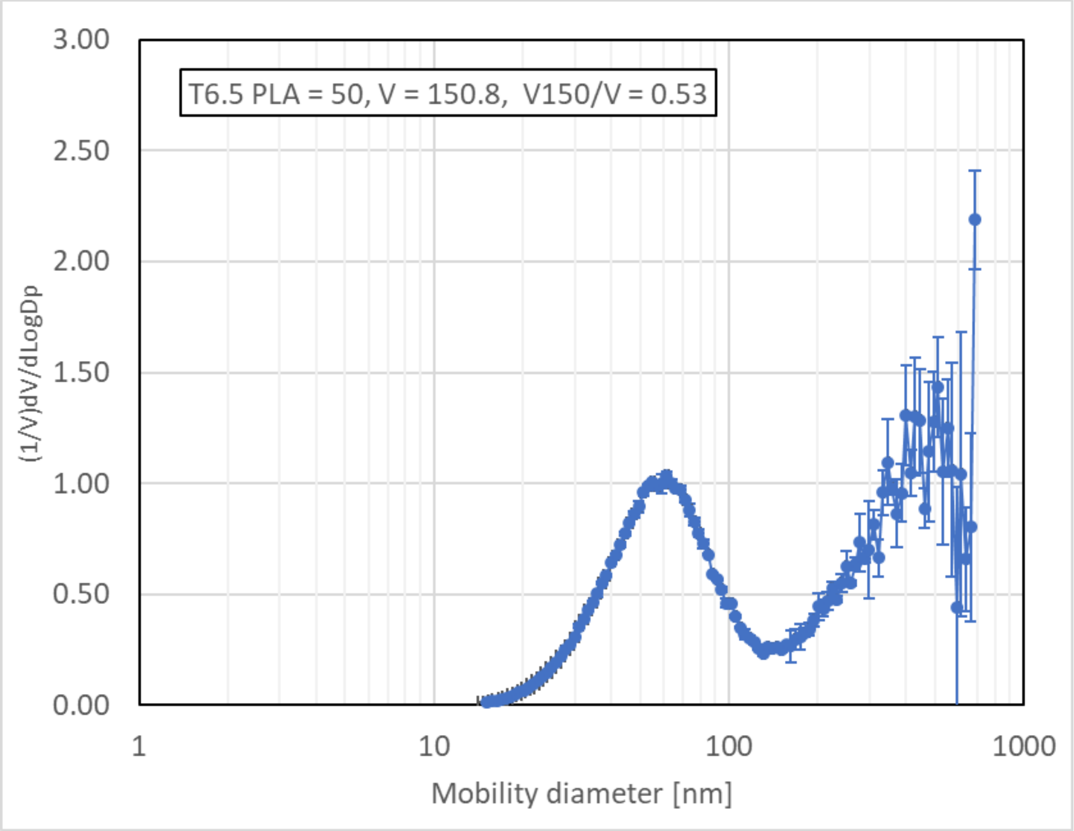


Coarse fraction decreases with increasing volume concentration and increases with camelina fraction, again T6.x is unusually high



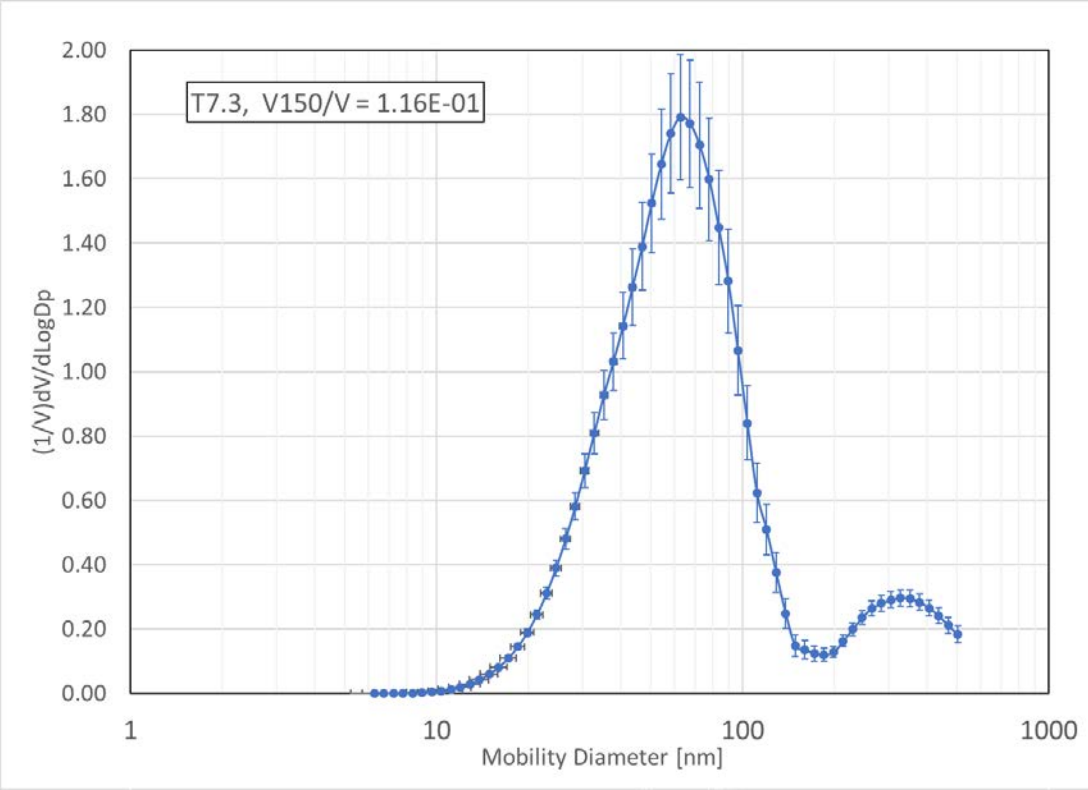
J-85 Jet-A, PLA50, T6.5 much larger coarse fraction (150/V) than typical PLA50 case, T7.3

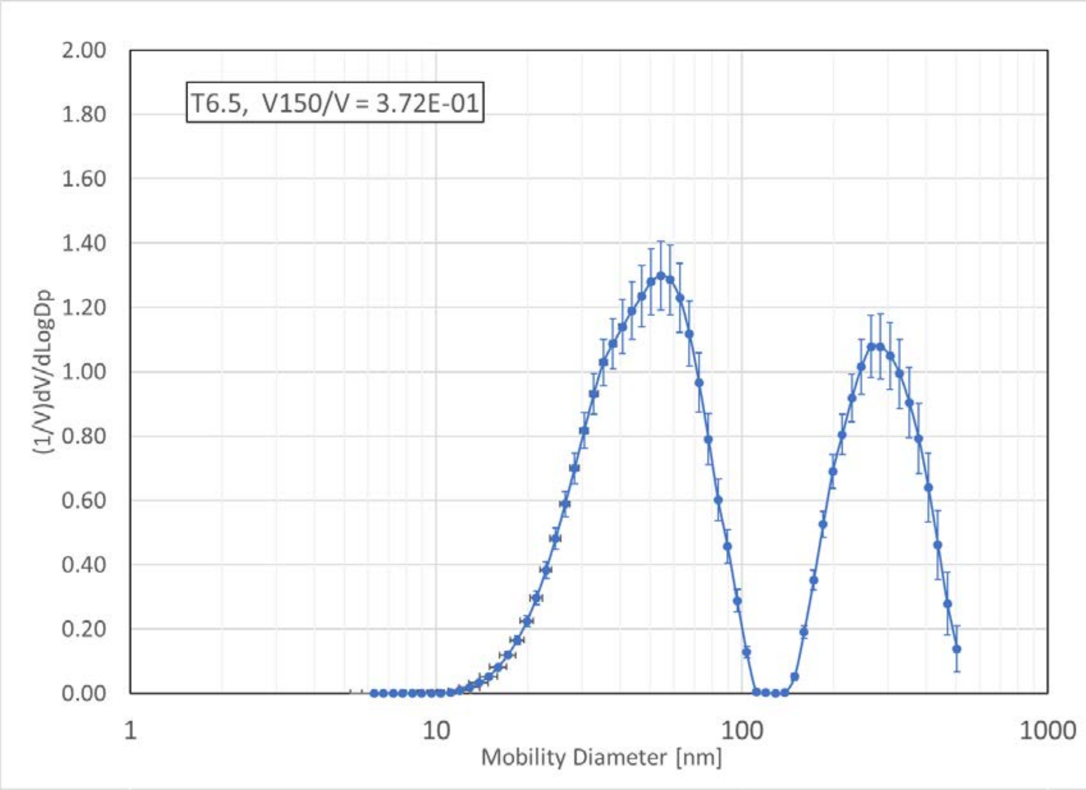




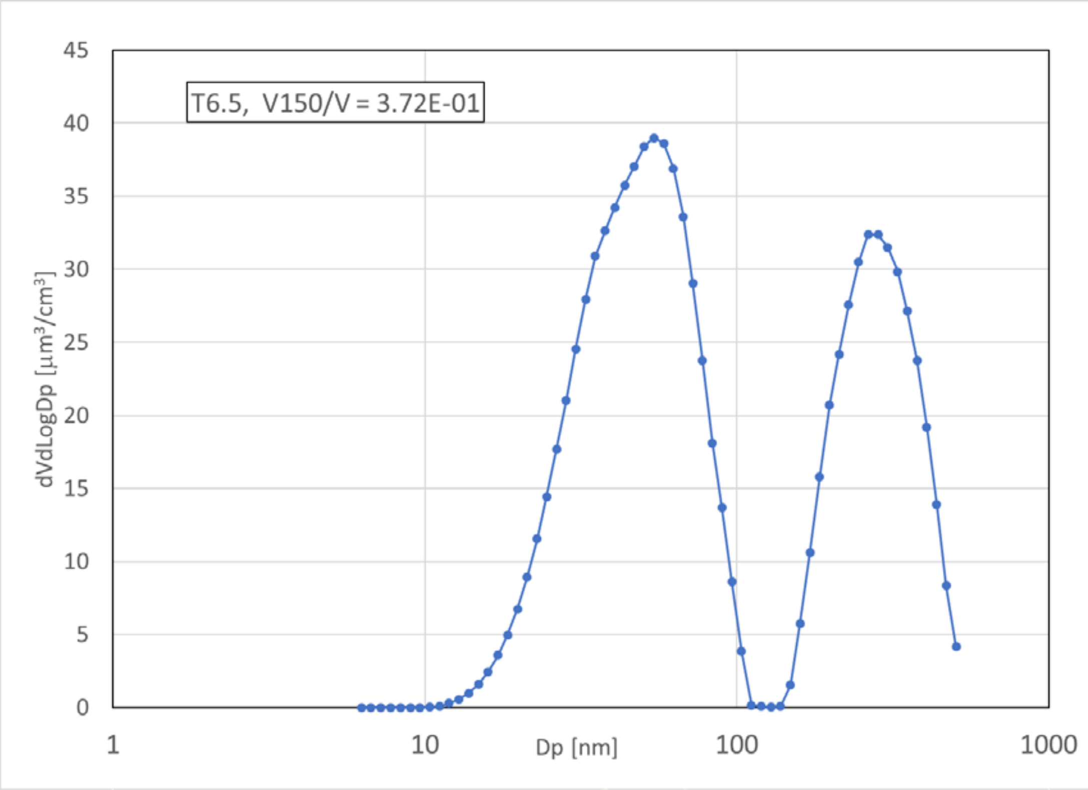
SMPS operated in low flow mode 0.3 Lpm/3 lpm – sizing range 15 to 690 nm
Size distributions normalized for easy comparison

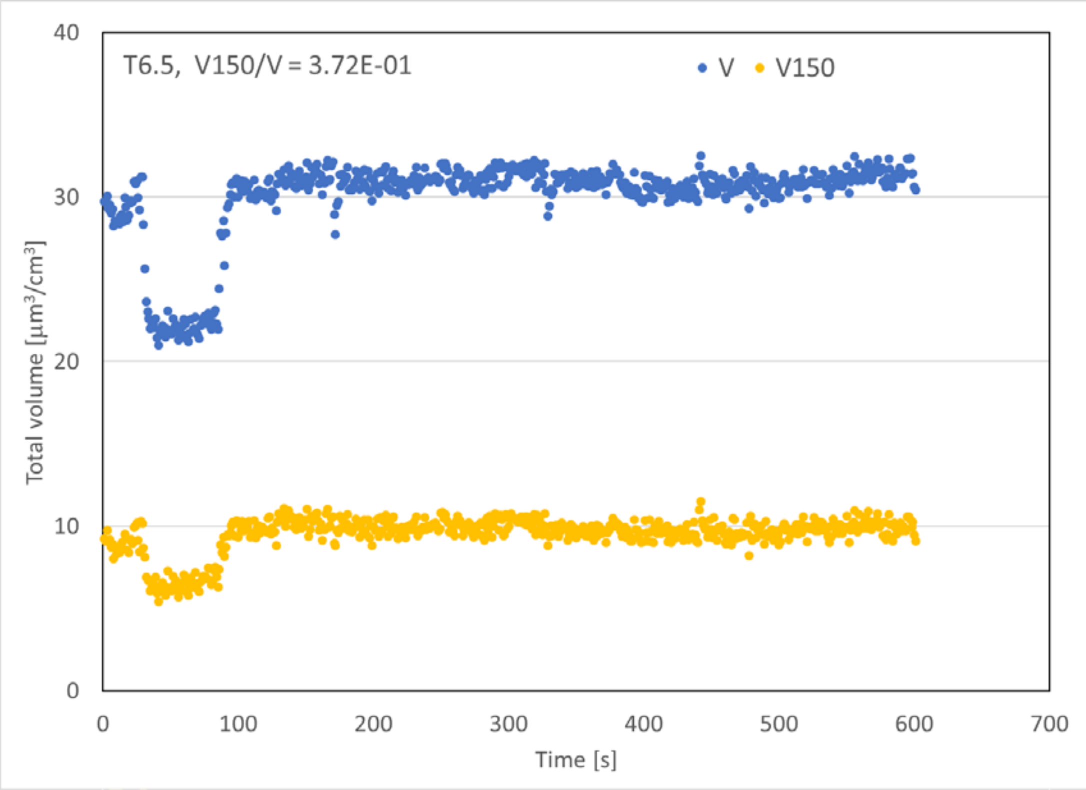
Like SMPS, EEPS shows large coarse fraction (V150/V) J-85, Jet-A, PLA50



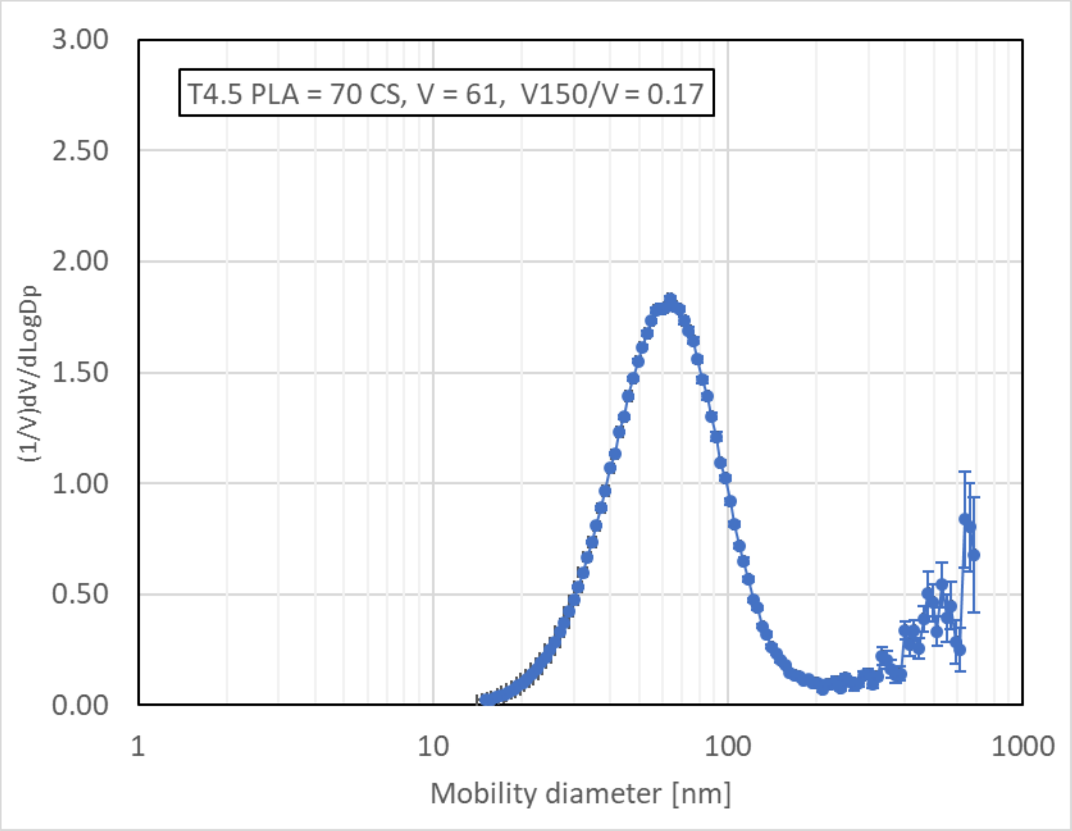


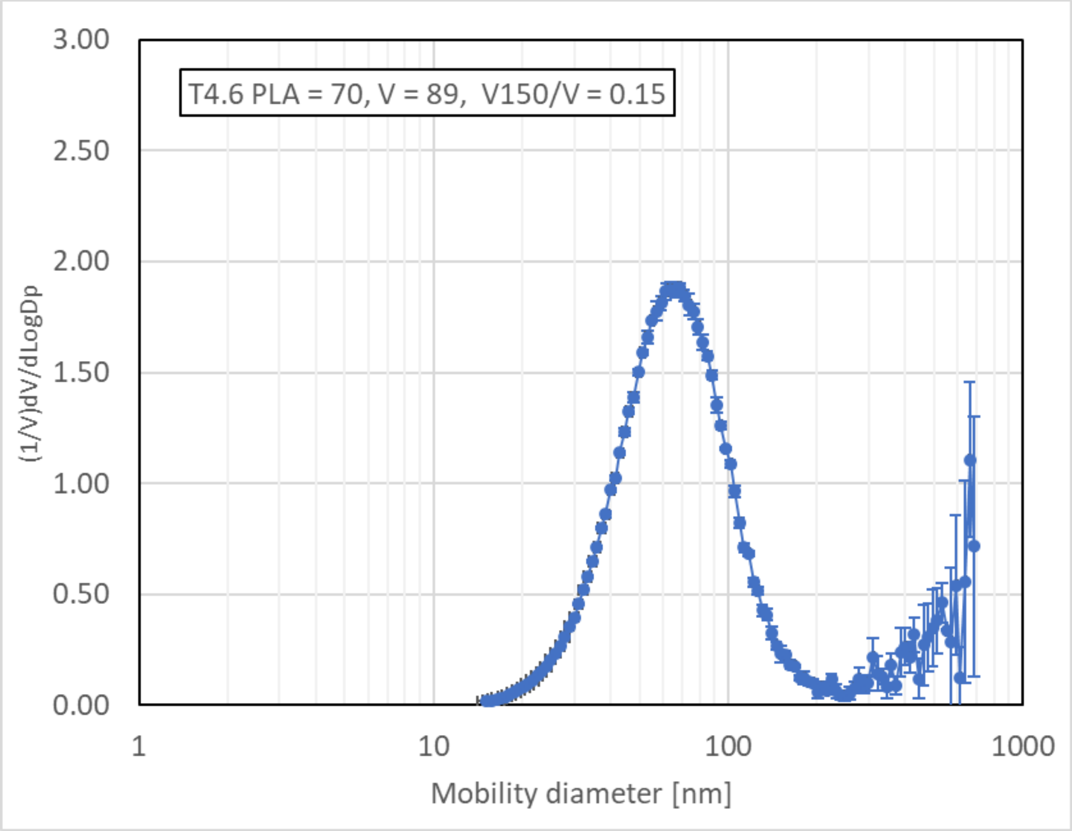
EEPS data, PLA50, J85, JetA, V150 tracks up and down with total V





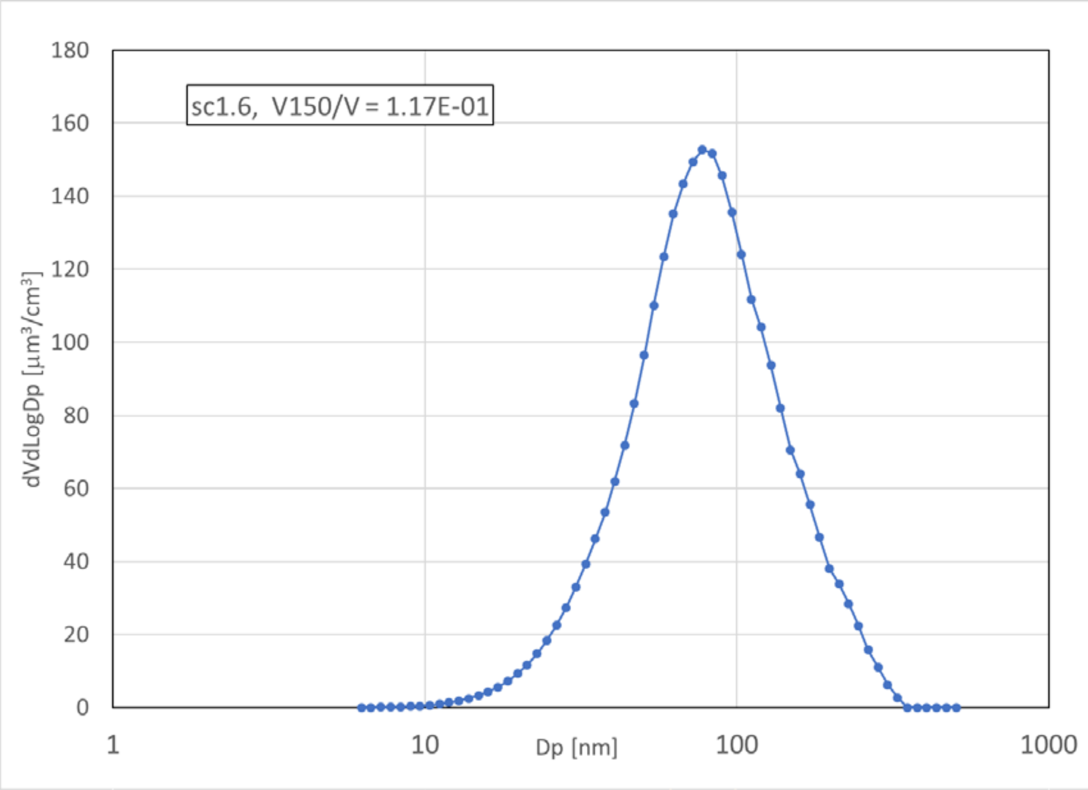
Properties of second mode – volatility, CS had no influence on V150/V for matched conditions

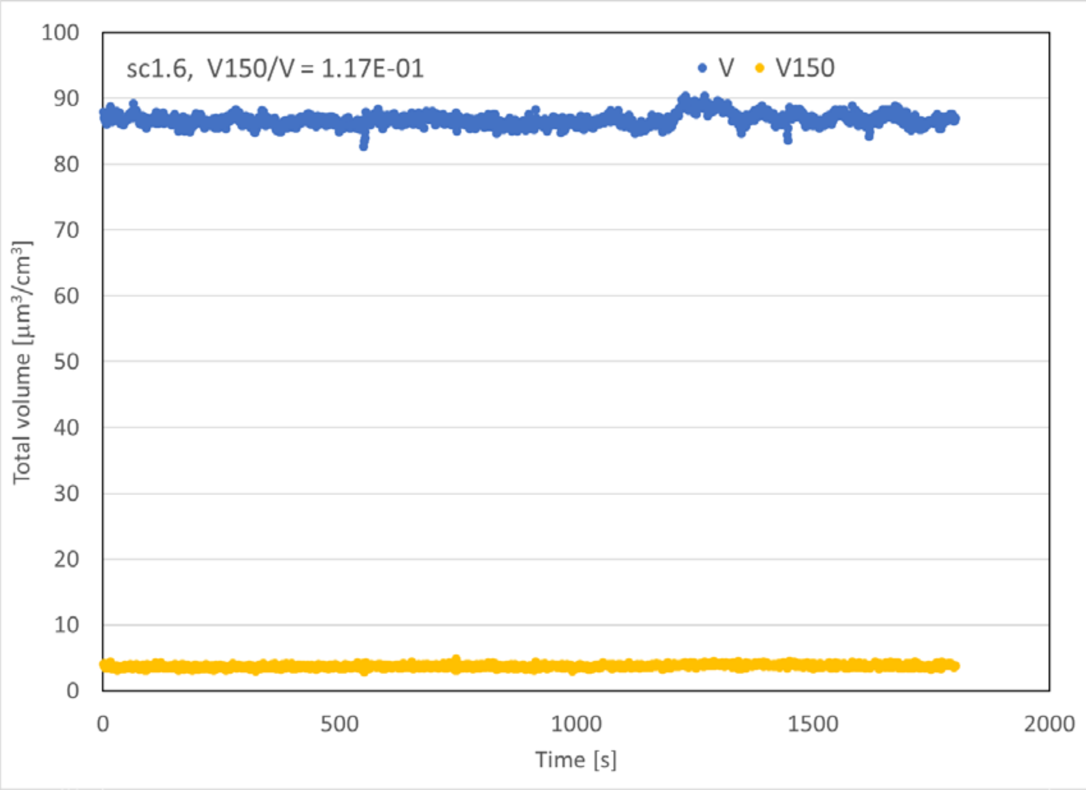




SMPS operated in low flow mode 0.3 Lpm/3 lpm – sizing range 15 to 690 nm
Size distributions normalized for easy comparison

Start cart APU operating on Jet A - unimodal





Origin and implications of second mode

- Instrument artifact?
  - No, shown by SMPS, EEPS, and DMS
- Sampling system artifact?
  - Particle deposition / resuspension? – no evidence of shedding in long runs
  - Start cart tests show using same sampling system show little evidence of coarse mode
- Second mode associated with J85 engine, not sampling system
  - Largest fraction for light load, low concentration
  - Appears to be non-volatile
  - Particle deposition / resuspension within engine?
  - What makes mode especially large in T6 series?
- Related ongoing work
  - Single Particle Mass Spectrometer (SPMS) measurements by Alla Zelenyuk, PNNL
    - SPMS clearly shows 2 modes, a fractal soot mode and a larger diameter compact dense mode consisting of organics and ash, especially in series T6
    - The mass fraction in the second mode increases with decreasing load and may be significant
  - A major engine manufacturer reports a large second mode with its cleanest engines
- A large second mode will lead to large errors in line loss corrections using current method

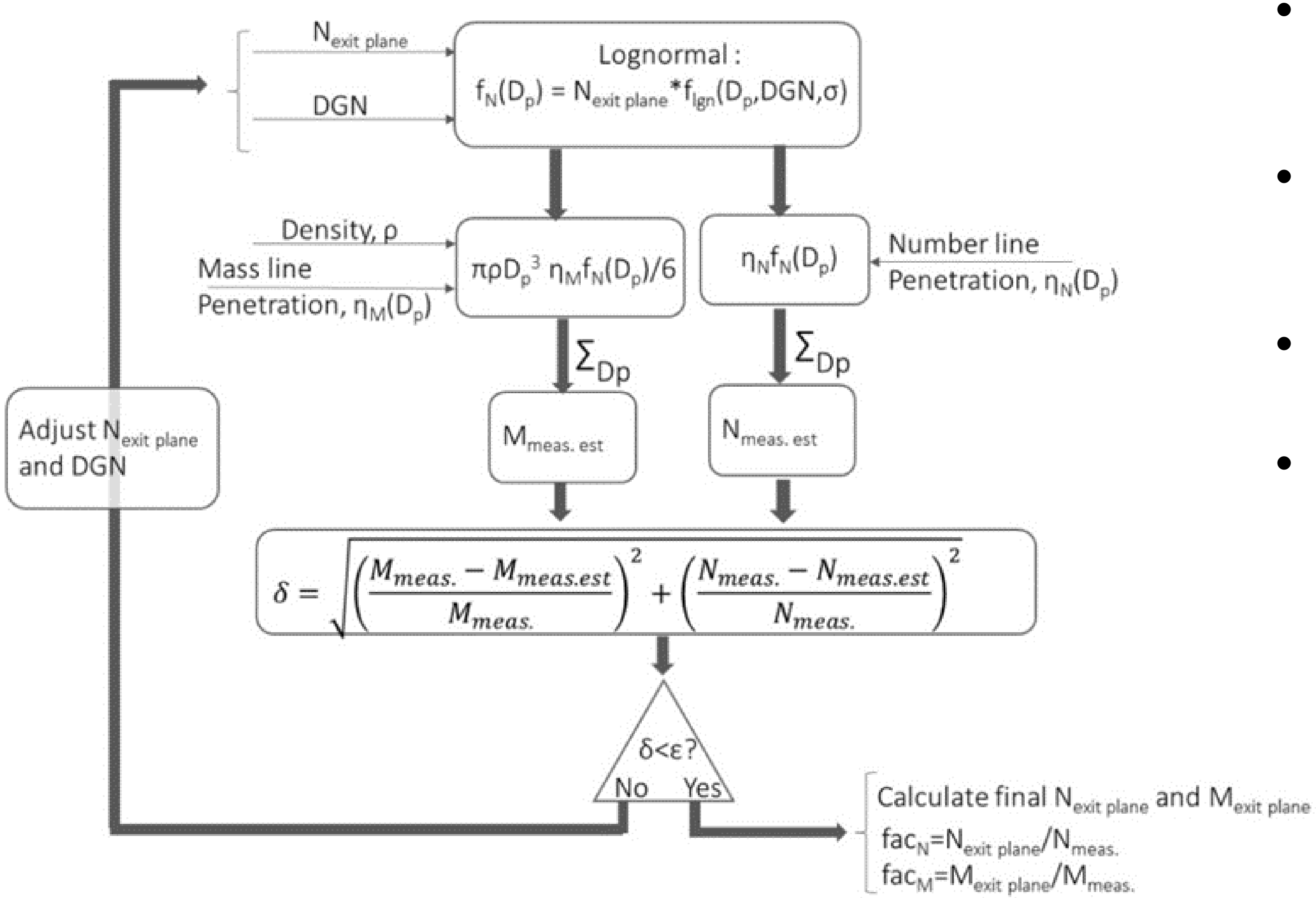
Study Participants

- U. S. Environmental Protection Agency National Risk Management Research Laboratory [NRMRL]--John Kinsey*
- U. S. Environmental Protection Agency National Vehicle and Fuel Emissions Laboratory [NVFEL]--Bob Giannelli, Jeff Stevens, Cullen Leggett and Nick Bies
- U. S. Air Force, Arnold Engineering Development Complex (AEDC)--Robert Howard, Mary Forde and Test Team
- U. S. Department of Energy, Pacific Northwest National Laboratory (PNNL)--Alla Zelenyuk-Imre and Kaitlyn Suski
- Artium Technologies--Greg Payne and Julien Manin
- Singularity Scientific--Richard Frazee
- Aerodyne Research--Tim Onasch and Andrew Freedman
- University of Minnesota--David Kittelson and Jake Swanson
- Penn State University—Randy Vander Wal, Madhu Singh, and Raju Kumal
- Instrument loans--Honeywell (D. Christie); NASA-Glenn (J. Klettlinger); TSI (R. Anderson); and Cambustion (C. Nickolaus)

* Retired; NRMRL is now known as the Center for Environmental Measurement and Modeling

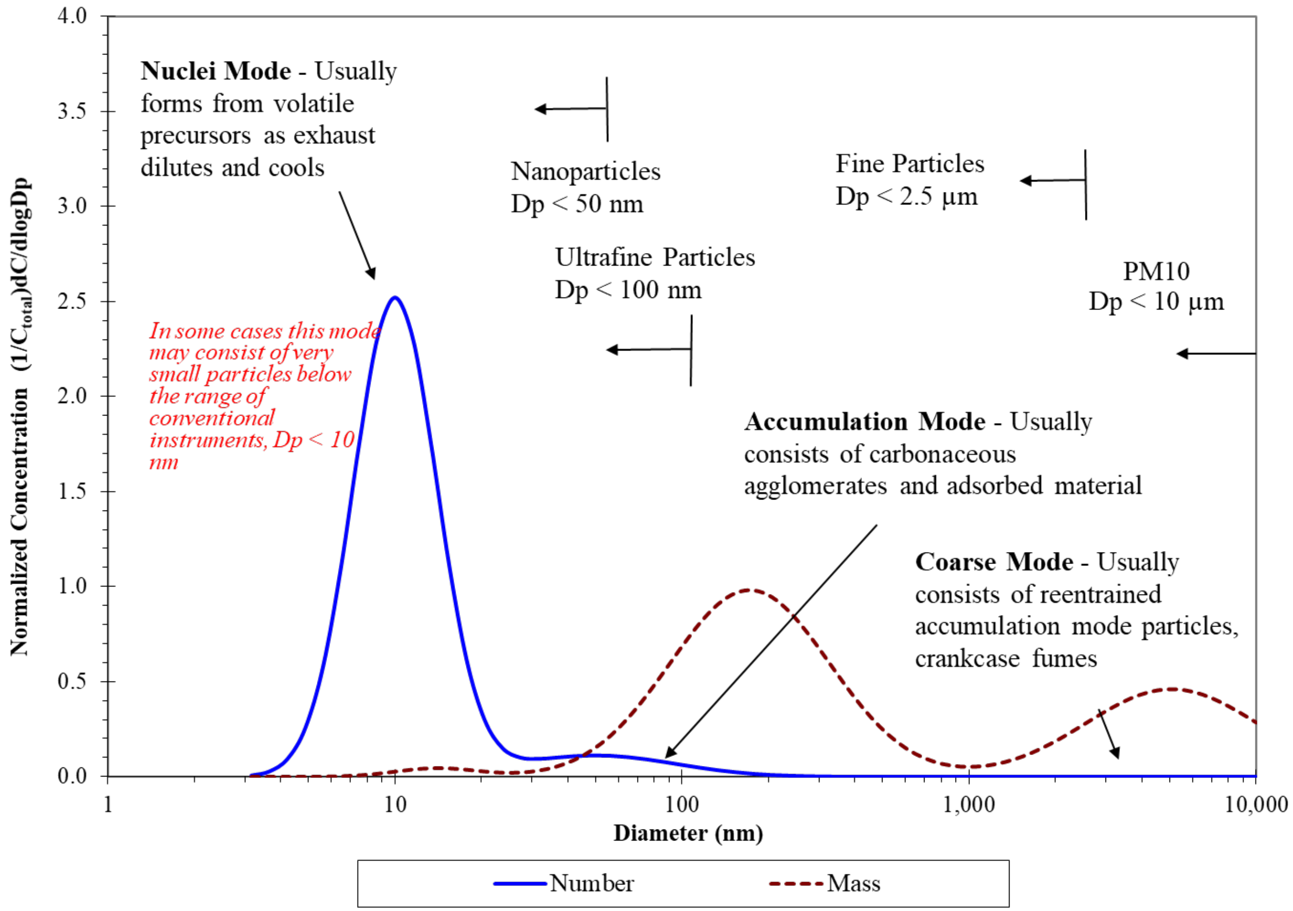
Backup slides

Line loss correction method

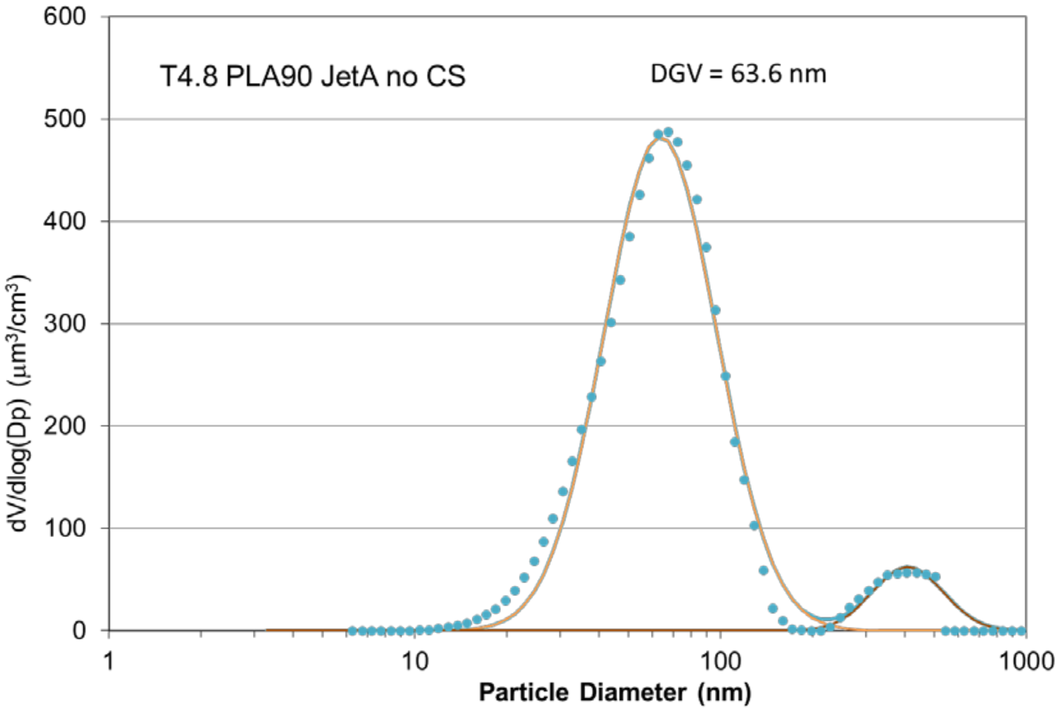


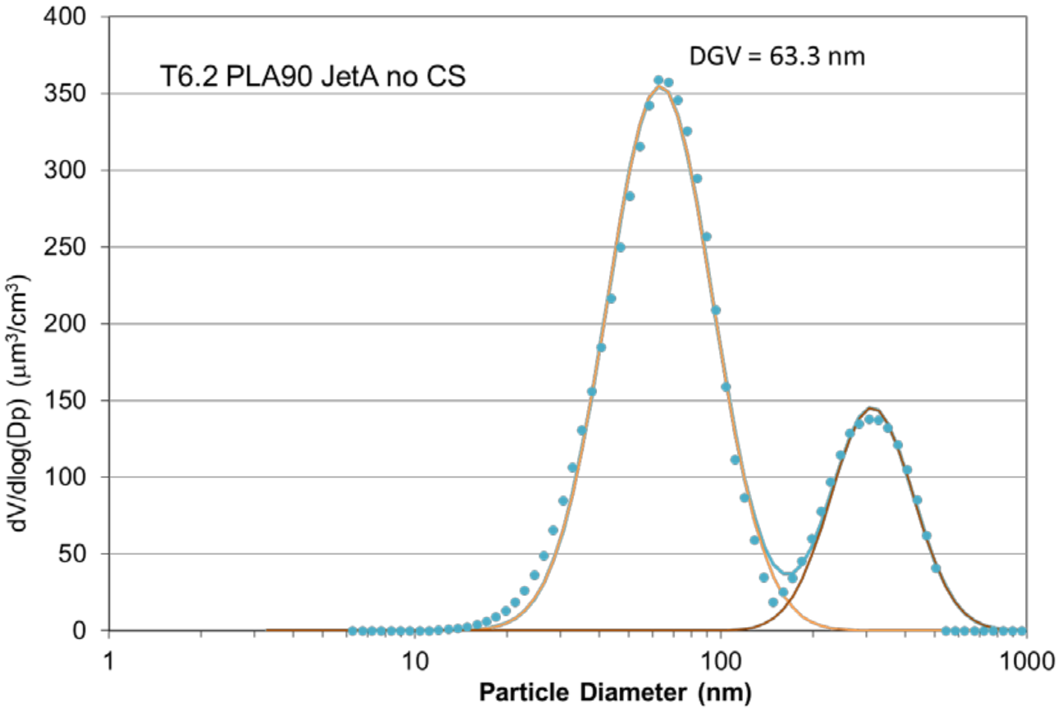
- Size dependent corrections are required but the SAE E-31 committee decided against direct particle size measurement
- The only measurements available are nonvolatile particle mass and number (nvPM and nvPN)
- Requires well validated line loss model, currently uses UTRC model
- Assumptions
  - No nucleation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

Typical piston engine exhaust particle size distribution by number and mass weighting



Second mode – EEPS data, bimodal fit
VARIAnT 4, J85, JetA, no CS, *PLA90 - range*





Second mode – EEPS data, bimodal fit VARIAnT 4, J85, JetA, no CS, *PLA50 - range*