Diesel and Gas Turbine Nanoparticle Density Distribution Measurements

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)

21st ETH Conference on Combustion Generated Nanoparticles

Zurich, Switzerland

June 19th – 22nd 2017

Acknowledgements

This work is part of the large study "Variable Response In Aircraft non-volatile PM (nvPM) Testing (VARIAnT) 3" with many 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, Nick Bies, Jeff Stevens, and Scott Agnew
- U. S. Air Force, Arnold Engineering Development Complex (AEDC)--Robert Howard, Brandon Hoffman, Brad Winkleman, Robert Baltz, Mary Forde, Todd VanPelt, and Test Team
- Artium Technologies--Greg Payne and Will Bachalo
- AVL Test Systems, Inc.--Richard Frazee
- Aerodyne Research--Tim Onasch and Andrew Freedman
- University of Minnesota--David Kittelson
- Southwest Research Institute [SwRI]--Imad Khalek, Huzeifa Badshah, Daniel Preece, and Vinay Premnath
- WMS Engineering--Bill Silvis

VARIAnT 3 Overall Study Goals

- Investigate the response of black carbon instruments: LII, MSS, MSS+, and CAPS PMssa
  - As challenged by various Diffusion Flame Combustion Aerosols (DFCASs) and fuels (anticipating changes in size distribution, apparent density, and morphology of the test aerosol particles)
  - Directly varying the concentration at each steady-state DFCAS operating condition
  - Varying the organic carbon/elemental carbon (OC/EC) ratio of the test aerosol with and without an inline catalytic stripper
  - Collect particle samples for assessment of morphology using TEM analysis
  - **Perform CPMA/DMA measurements for assessment of particle density versus size**
- If possible, assess whether the CAPS PMssa and LII and MSS with sensitivity improvements still meet type certification requirements

Overall Study Scope

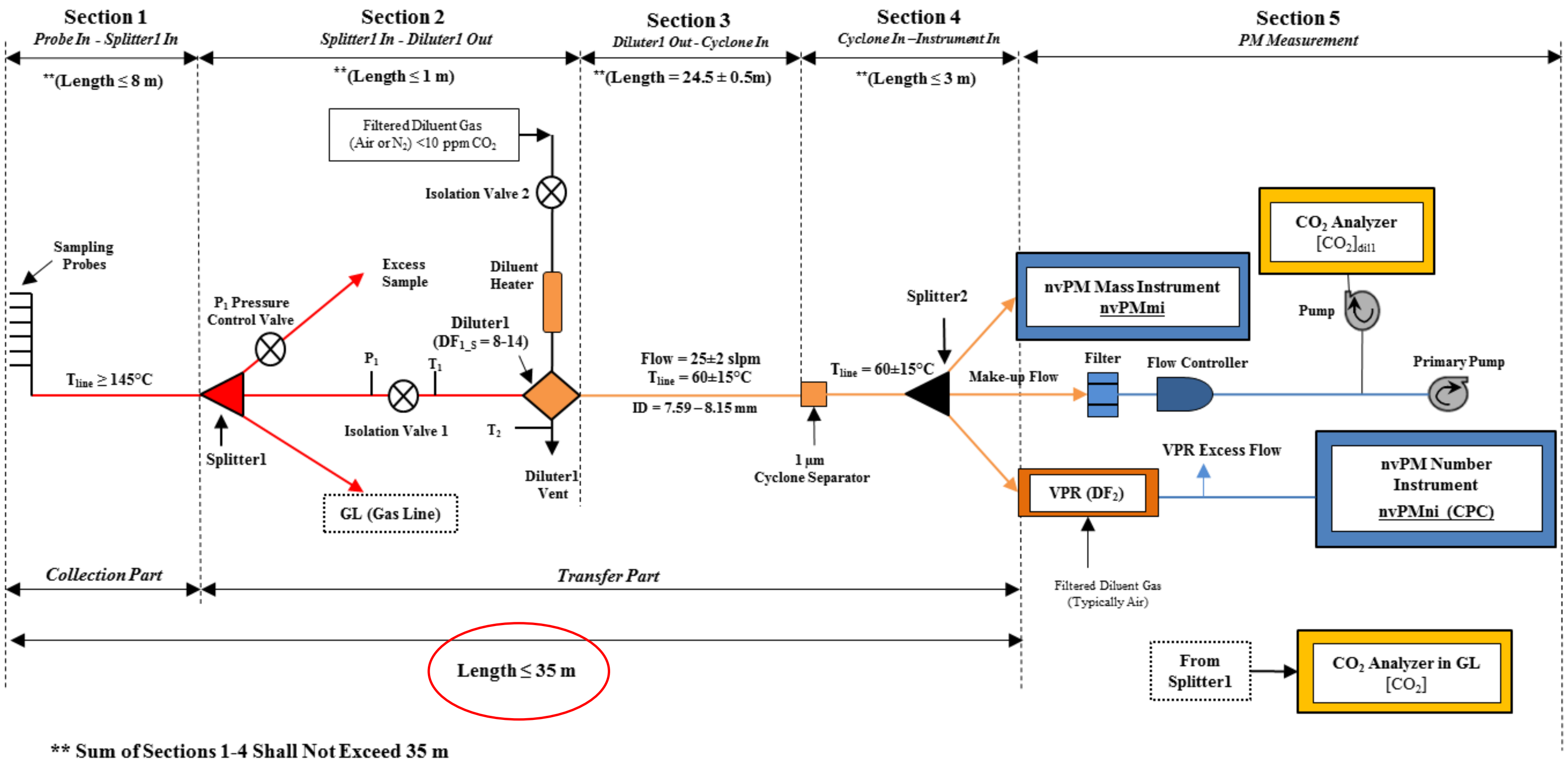
- Multiple DFCASs:
  - 2013 Cummins Model ISX15 heavy duty diesel engine (NVFEL)—engine out only
  - Libby Welding Company (AiResearch) Model GT-05 gas turbine start cart (AEDC/UTSI)
  - Libby Welding Company (AiResearch) LGT-60 gas turbine start cart (AEDC/UTSI)
  - J-85-GE-5 gas turbine (AEDC/UTSI)
  - ISUZU 4LE2T diesel engine generator set (AEDC/UTSI)
- Multiple fuel types:
  - ULSD Certification diesel fuel (ISX15)
  - 100% Hydrogenation-Derived Renewable Diesel (HDRD) fuel (ISUZU)
  - 50% HDRD/Jet-A blend (LGT-60)
  - Jet-A (GT-05, LGT-60, and J-85)
  - 45% Camelina/Jet-A blend (LGT-60 and J-85)
  - 70% Camelina/Jet-A blend (J-85)

Motivation for density measurements

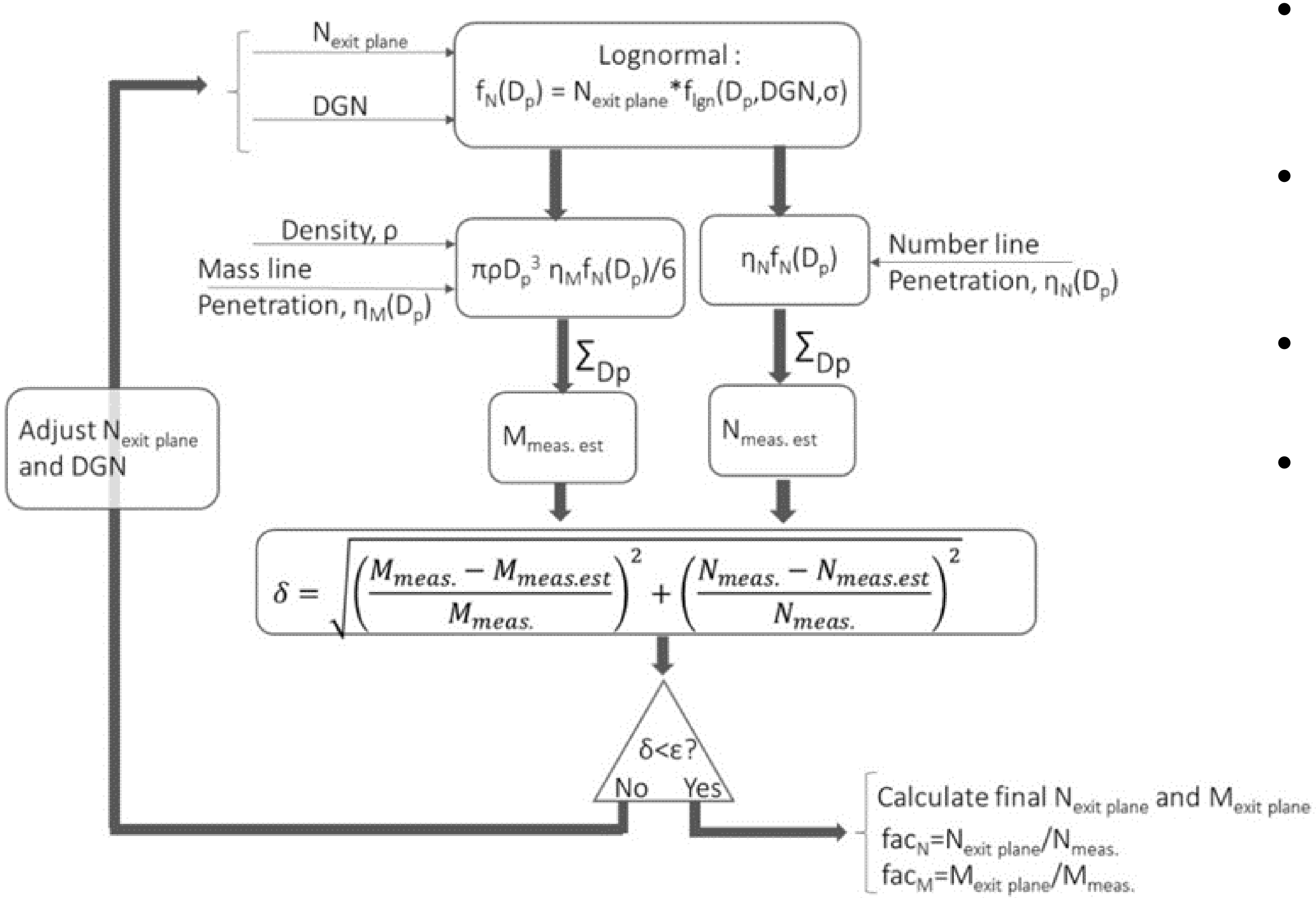
- New standards for aircraft particle mass. Particle number, and CO_2 are planned for 2020
- Particle standards are to be based on solid particle number larger than 10 nm , and solid particle mass
- Sampling conditions are brutal, imagine sampling from an exhaust stream at Mach 1 and 900 K with engines producing up to 530,000 N (120,000 lbf) thrust
- This necessitates very long sampling lines, up to 35 m, leading to significant particle losses, especially for particle number
- Thus line loss corrections must be made – these corrections require knowledge of (among other things) particle density

Long sampling lines necessitate a line loss correction which requires knowledge of density

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



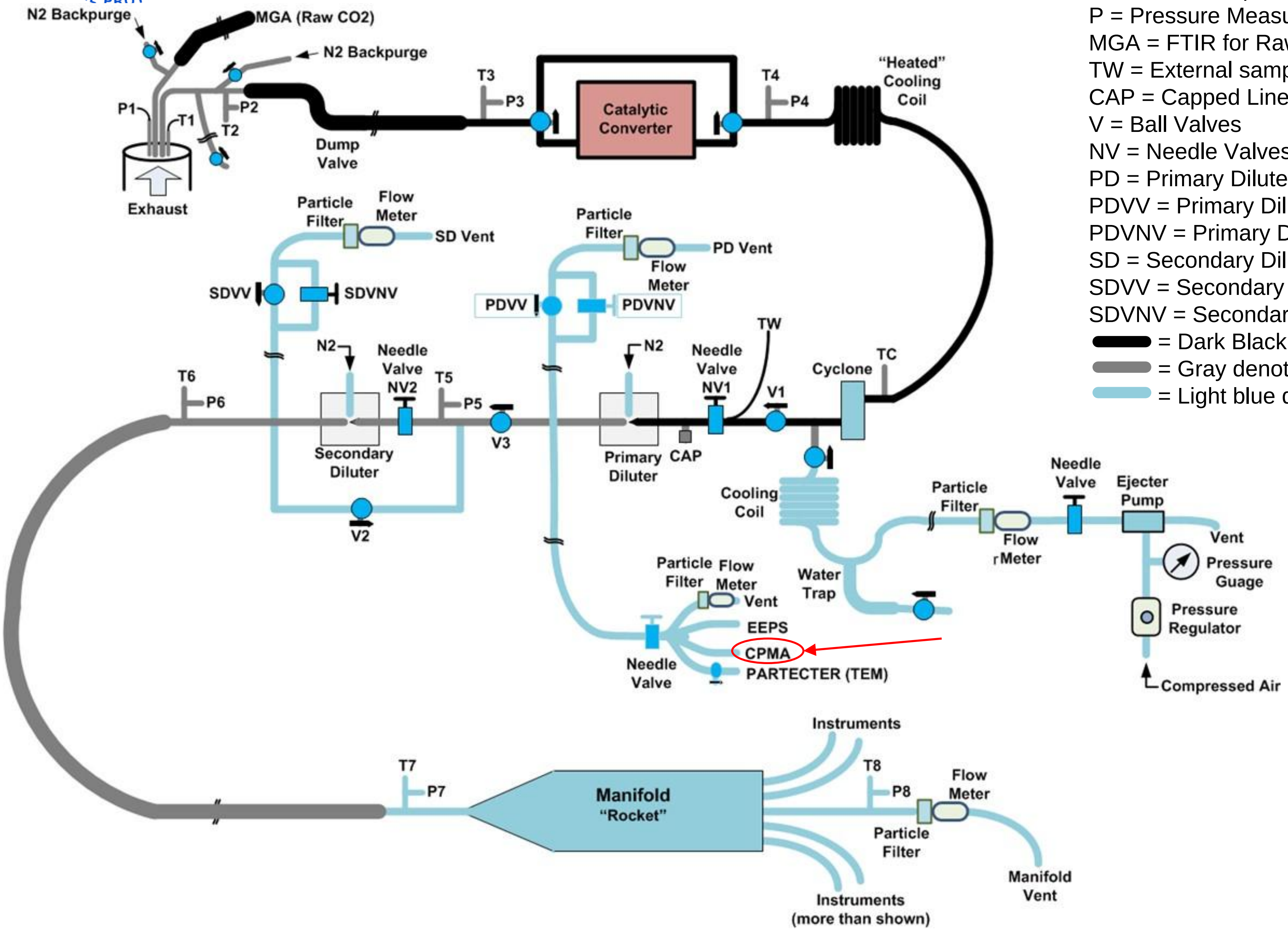
Line loss correction method

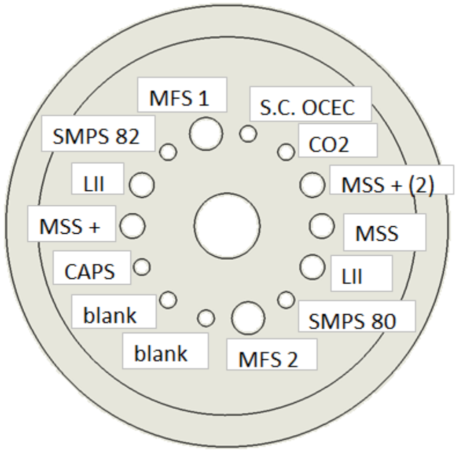


- Size dependent corrections are required but the SAE E-31 committee decided against direct particle size measurement
- The only measurements available are nonvolatile particle mass and number (nvPM and nvPN)
- Requires well validated line loss model, currently uses UTRC model
- Assumptions
  - No nucleation 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

Sampling System Schematic for AEDC

T = Thermocouple Temperature Measurement
P = Pressure Measurement
MGA = FTIR for Raw CO_2 & other gaseous concentrations)
TW = External sampling tube temperature
CAP = Capped Line
V = Ball Valves
NV = Needle Valves
PD = Primary Diluter
PDVV = Primary Diluter Vent Valve
PDVNV = Primary Diluter Vent Needle Valve
SD = Secondary Diluter
SDVV = Secondary Diluter Vent Valve
SDVNV = Secondary Diluter Vent Needle Valve
= Dark Black denotes line segments actively heated to ~160 °C
= Gray denotes line segments actively heated to ~ 60 °C
= Light blue denotes line segment not actively heated (some wrapped)





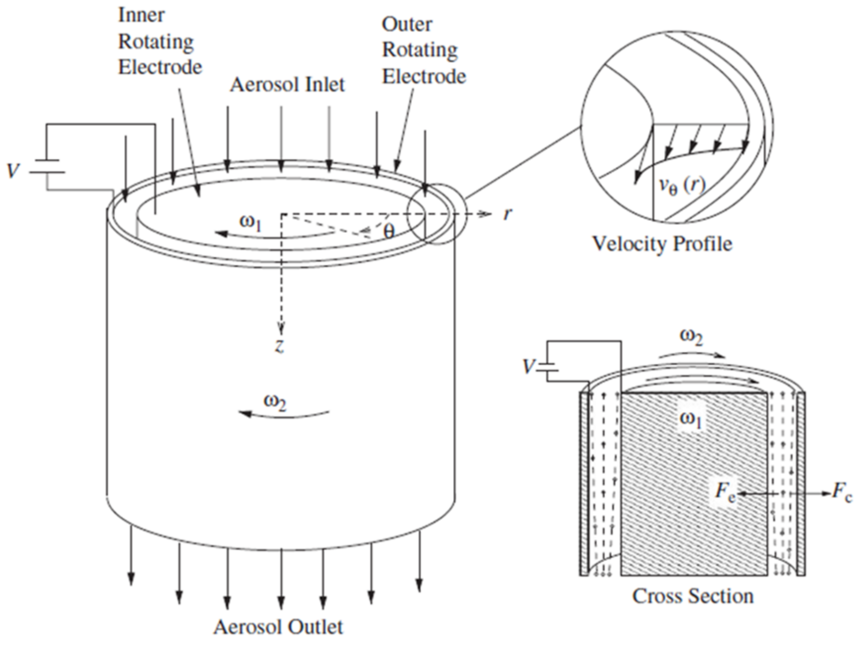
Manifold Outlets

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 nonvolatile PM (nVPM) or “solid” particles
- Concentration varied over wide range by varying dilution ratio

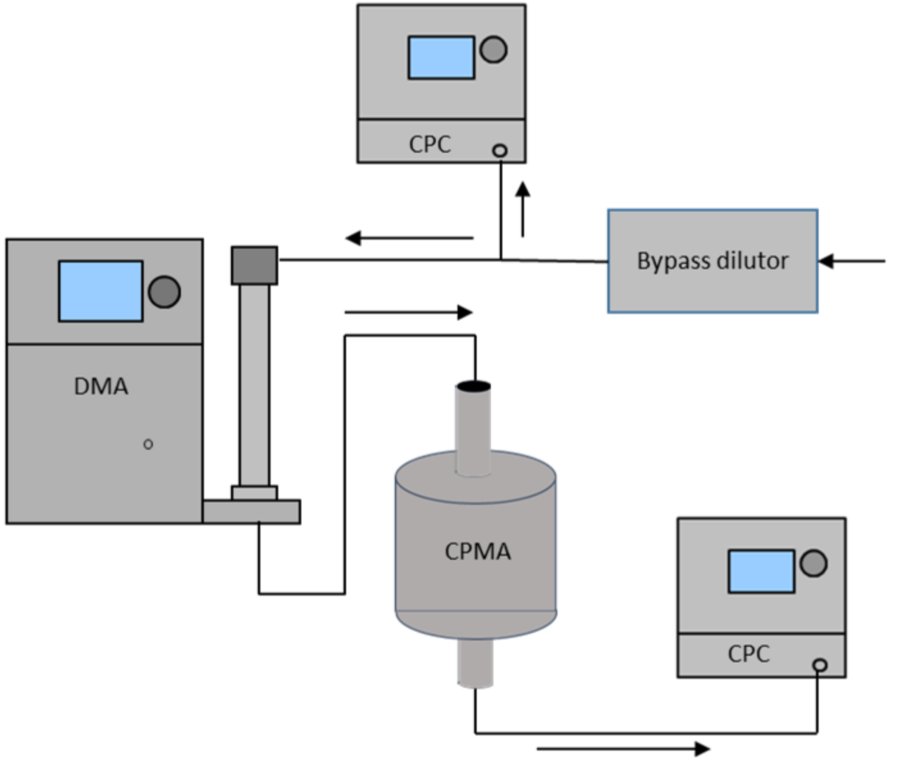
Apparatus for CPMA measurements



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

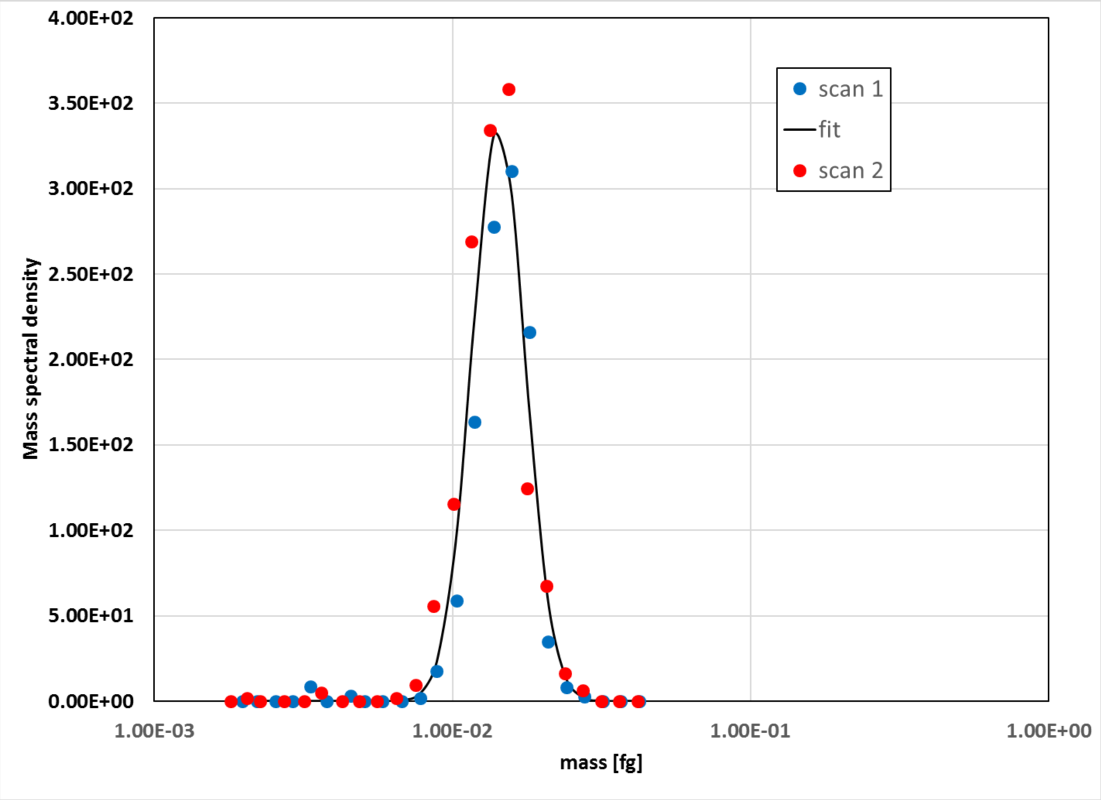
$$\frac{m}{N_q} = \frac{eV}{r^2 \omega^2 \ln\left\{ r_o / r_i \right\}}$$

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



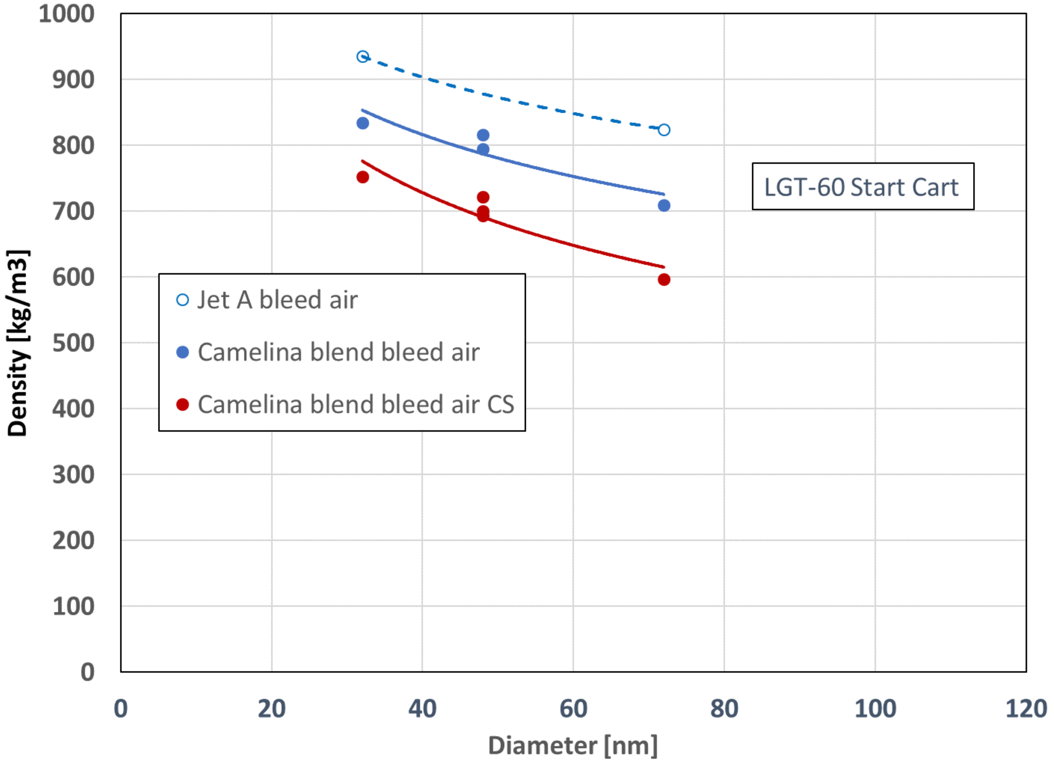
Typical data: LGT-60 start cart bleed air (load) on

intensity	x bar	ln x bar	sigma	ln sigma	pre exp	ChiSqrTotal					
122.52	0.0143	-4.25	1.16	0.15	2.74	2.43E+04					
	average	scan 1	scan 2								
mean	0.0141	0.0145	0.0136			Scan 1	Particle diameter (n	31.96			
mode	0.0157	0.0158	0.0155			Scan 2	Particle diameter (n	31.98			
median	0.0143	0.0148	0.0137			average		31.97			
Datum#	Time	Mass (fg)	Mass Spectral Density (dN/dLog(Mp*)/cc)	lognorm	ChiSqr						
1	14:03:51	4.23E-02	0.00E+00	2.87E-04	8.23E-08		V	1.71E+04	nm3	density	
2	14:04:06	3.68E-02	0.00E+00	8.53E-03	7.27E-05			1.71E-23	m3		
3	14:04:20	3.19E-02	0.00E+00	1.57E-01	2.46E-02		m	1.43E-02	fg		
4	14:04:34	2.78E-02	2.92E+00	1.79E+00	1.29E+00			1.43E-20	kg	8.34E+02	kg/m3
5	14:04:49	2.41E-02	8.12E+00	1.29E+01	2.30E+01						
6	14:05:04	2.09E-02	3.51E+01	5.92E+01	5.84E+02						
7	14:05:17	1.81E-02	2.16E+02	1.71E+02	2.02E+03						
8	14:05:30	1.58E-02	3.11E+02	2.99E+02	1.43E+02						
9	14:05:43	1.38E-02	2.78E+02	3.31E+02	2.85E+03						
10	14:05:57	1.18E-02	1.63E+02	2.21E+02	3.38E+03						
11	14:06:10	1.03E-02	5.87E+01	9.61E+01	1.40E+03						
12	14:06:24	8.86E-03	1.76E+01	2.28E+01	2.78E+01						
13	14:06:37	7.80E-03	1.63E+00	4.45E+00	7.94E+00						
14	14:06:50	6.75E-03	0.00E+00	4.46E-01	1.99E-01						
15	14:07:03	5.82E-03	0.00E+00	2.50E-02	6.25E-04						
16	14:07:17	5.06E-03	0.00E+00	9.84E-04	9.68E-07						
17	14:07:30	0.004557	2.959	6.75E-05	8.76E+00						
18	14:07:44	0.003793	0	3.19E-07	1.02E-13						
19	14:07:57	0.003332	8.461	4.50E-09	7.16E+01						
20	14:08:10	0.002913	0	3.56E-11	1.27E-21						
21	14:08:28	0.002555	0	2.10E-13	4.42E-26						
22	14:08:48	0.002207	0	4.21E-16	1.78E-31						
23	14:09:07	0.001977	0	2.83E-18	8.01E-36						

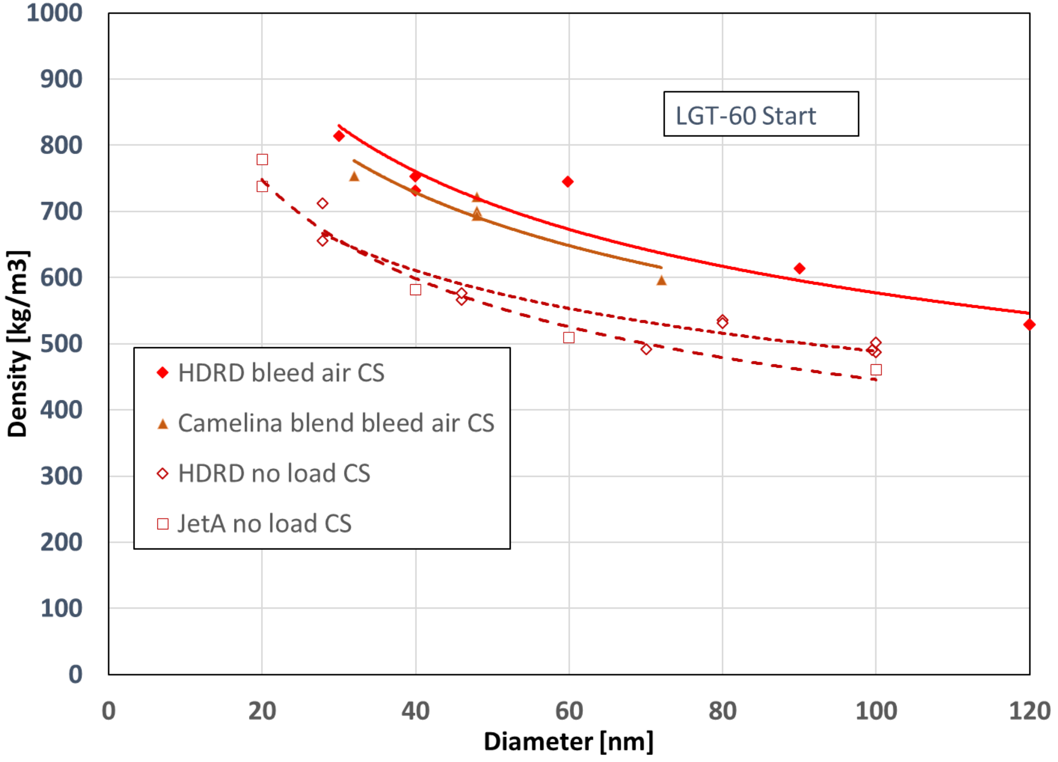


LGT-60 Start Cart – a small gas turbine engine

LGT-60 with/without CS, total (including semi-volatile) and solid particle density

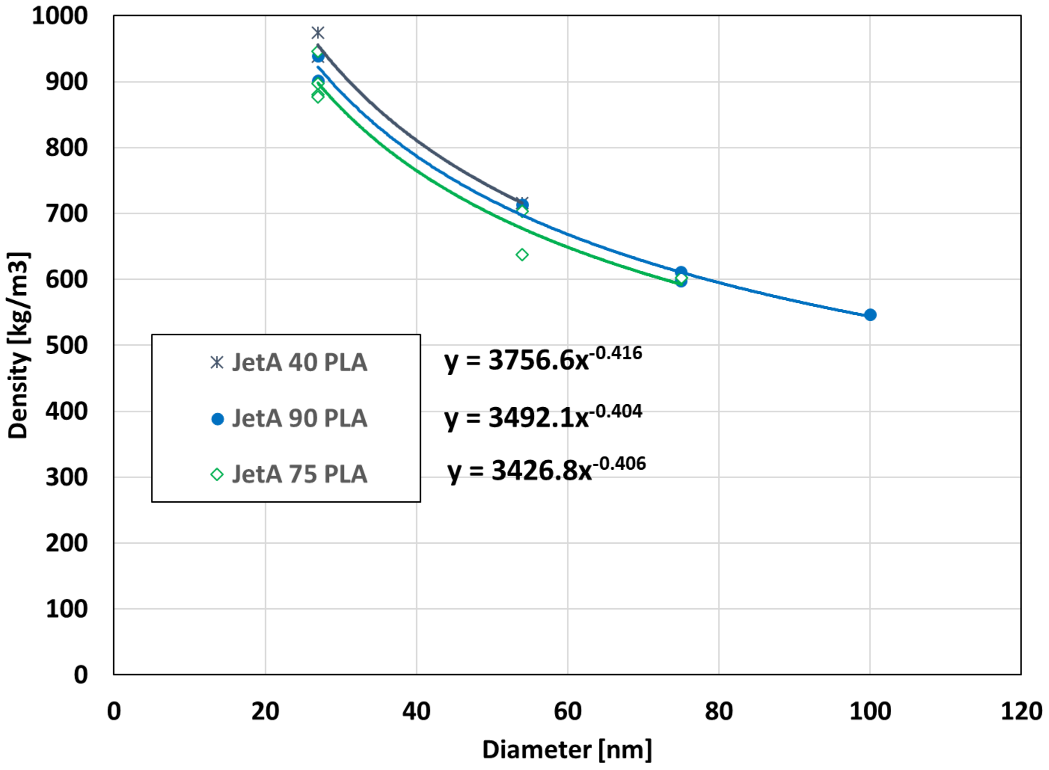


LGT-60 with CS, variable load and fuel, solid particle density

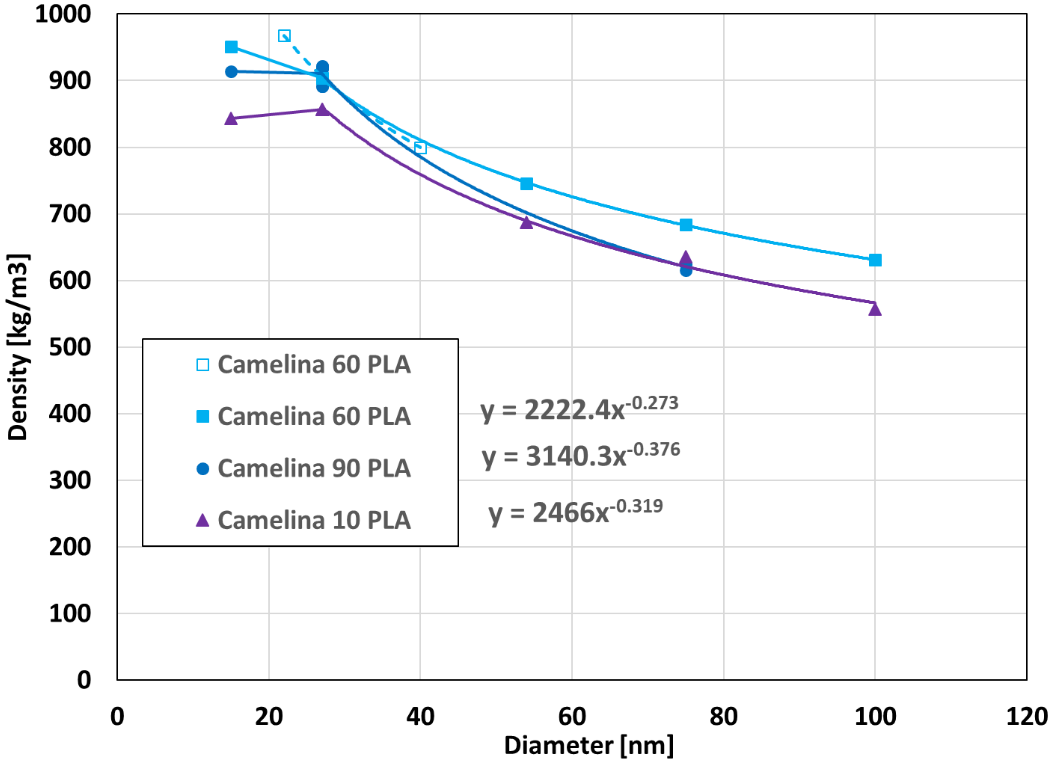


J-85 turbojet tests – influence of fuel type and engine load (10 PLA = idle, 90 PLA = max thrust)

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

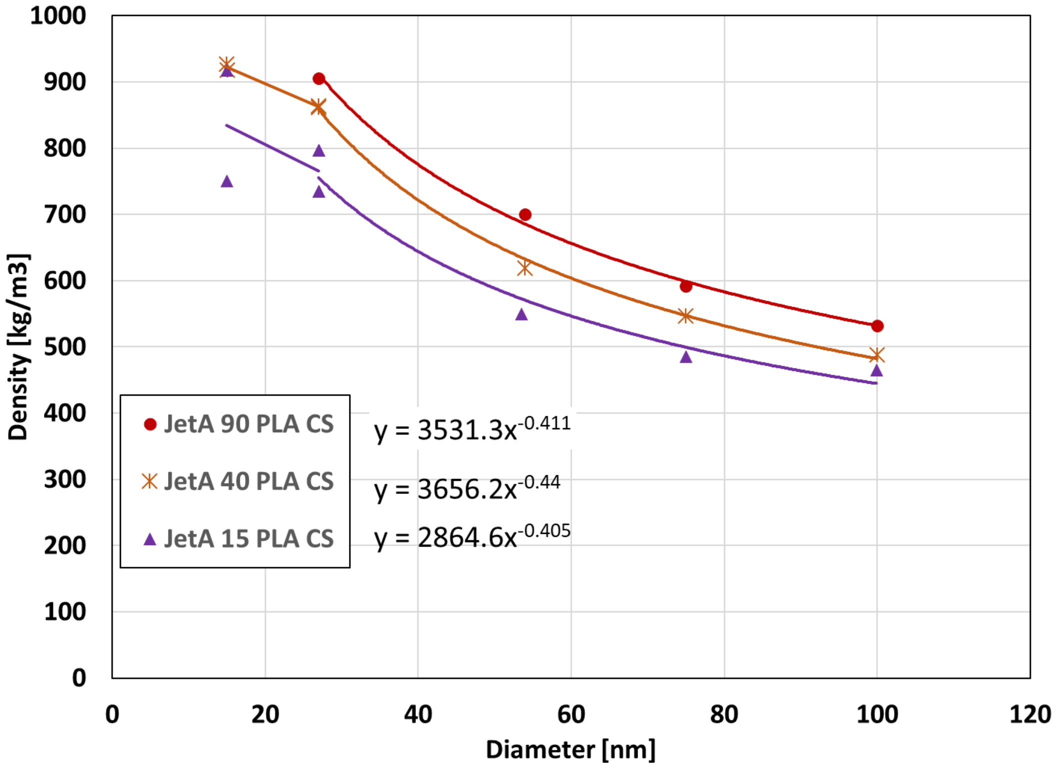


J-85 Camelina blend fuel, variable thrust without CS, total density

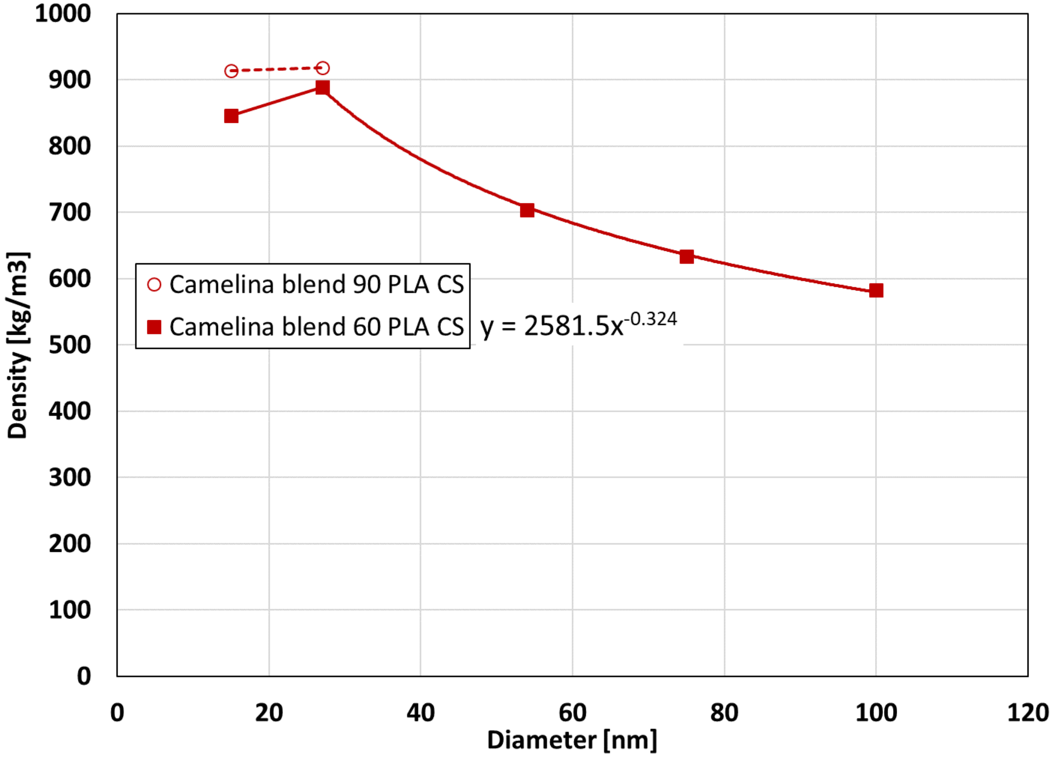


J-85 turbojet tests – influence of fuel type and engine load on solid particle density profiles

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

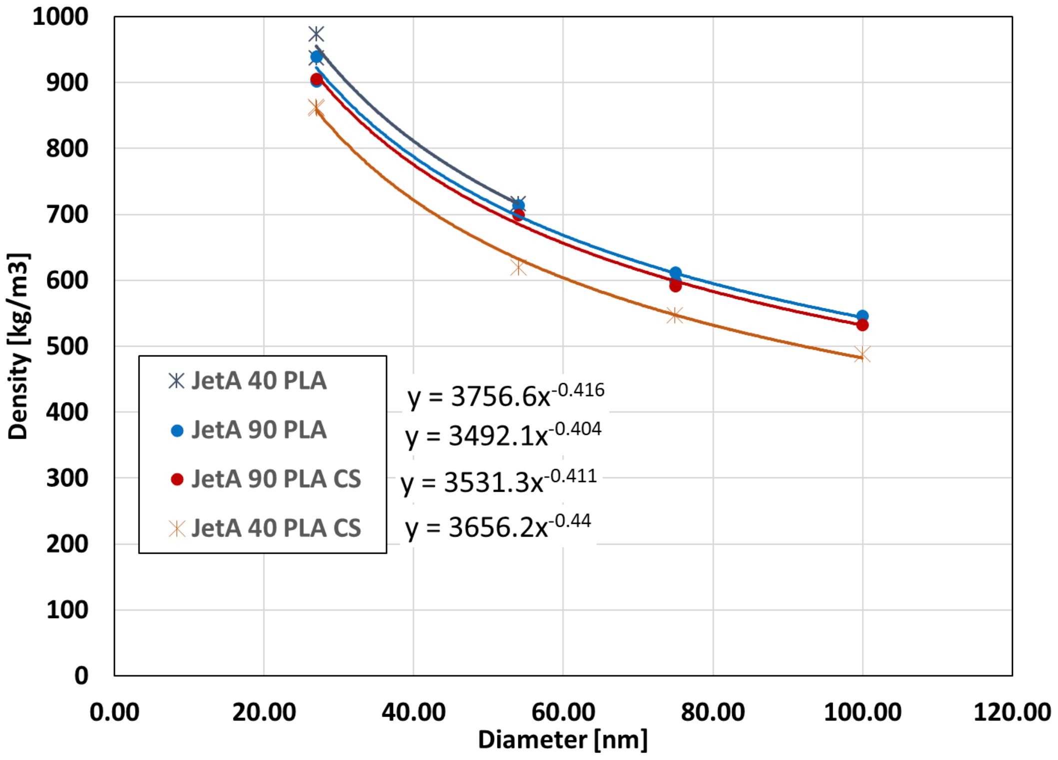


J-85 Camelina blend fuel, medium and high thrust with CS, solid density

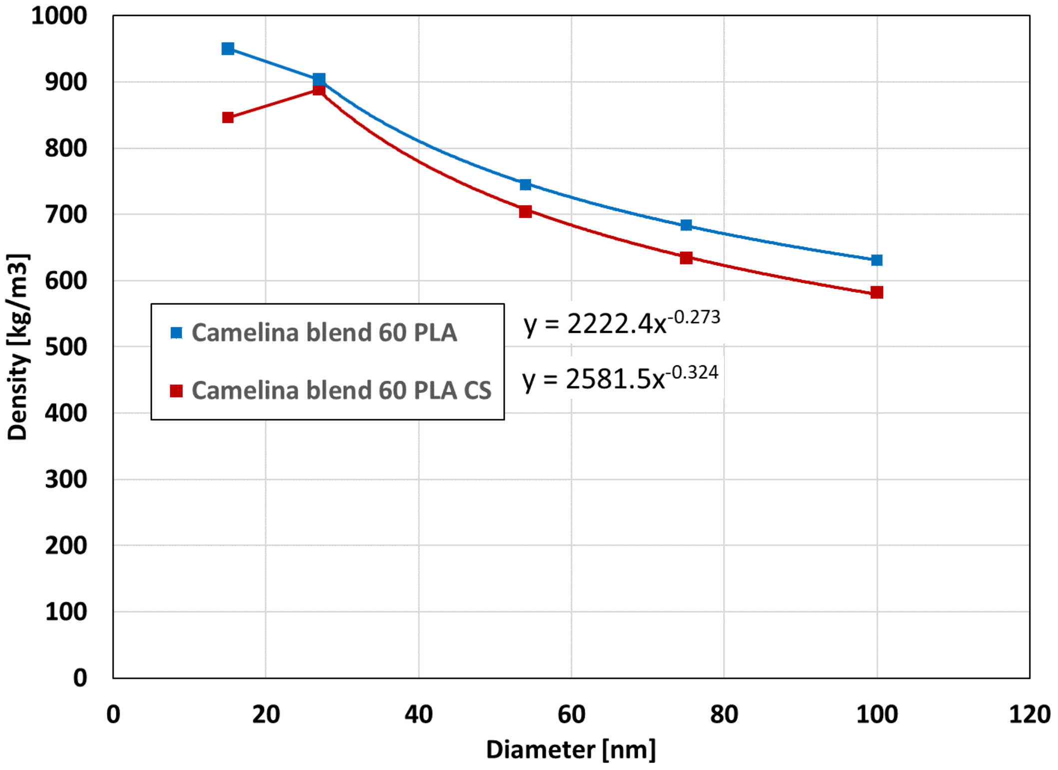


J-85 turbojet – influence of fuel type and engine load on semi-volatile fraction (10 PLA = idle, 90 PLA = max thrust)

J-85 jet-A fuel, medium and high load with/without CS

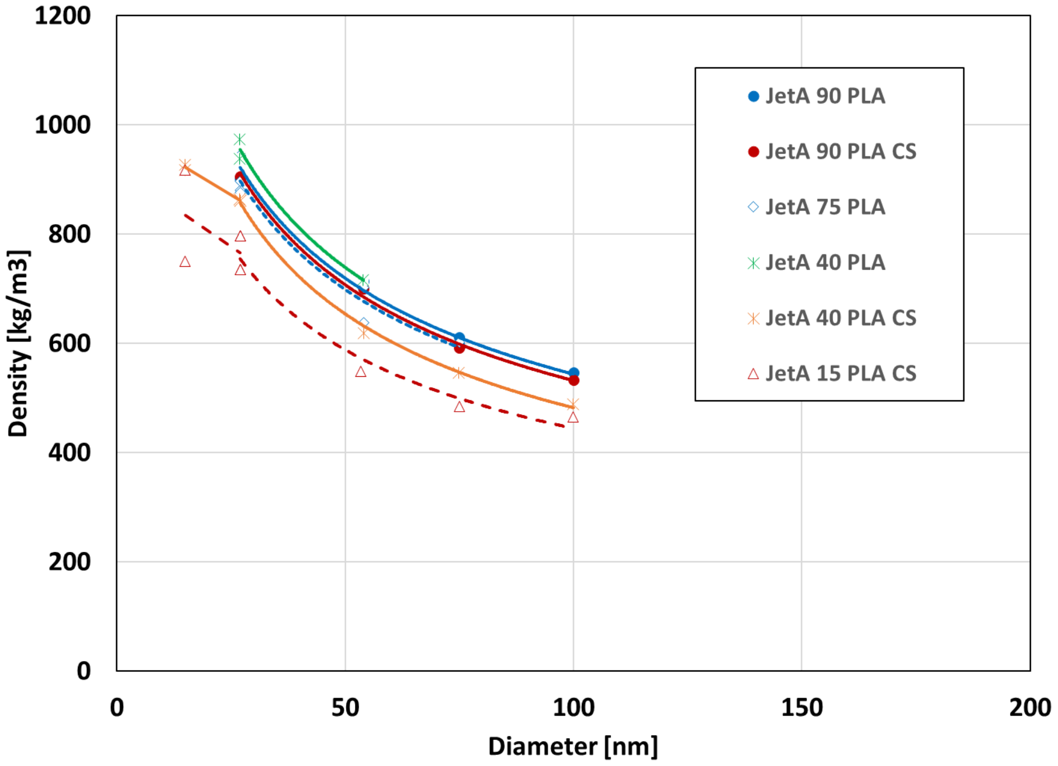


J-85 Camelina blend fuel, medium load with/without CS

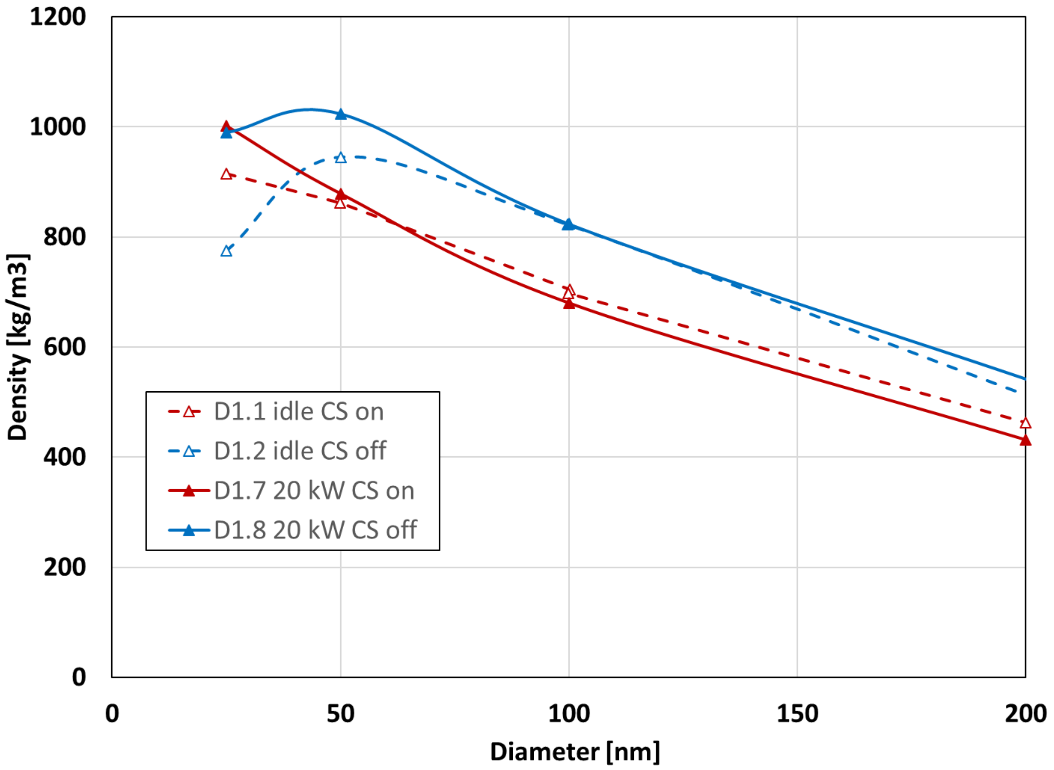


Isuzu diesel genset compared to J-85

J-85 Jet-A fuel, variable thrust, with/without CS

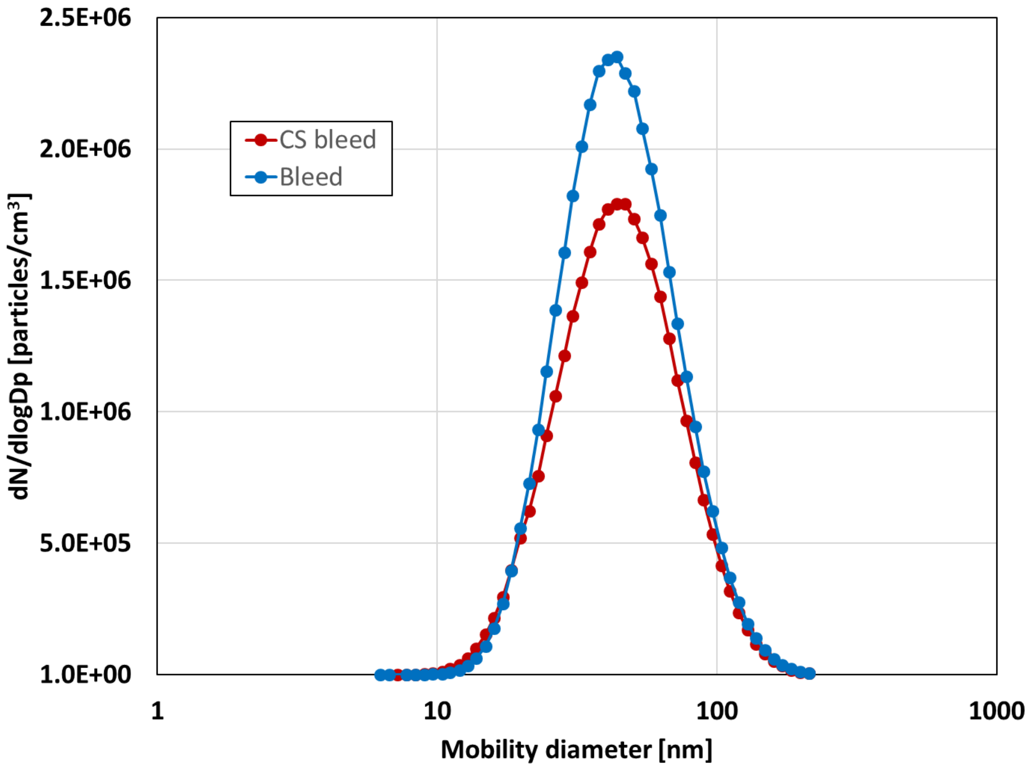


Isuzu diesel generator, HDRD fuel, idle and high power, with/without CS

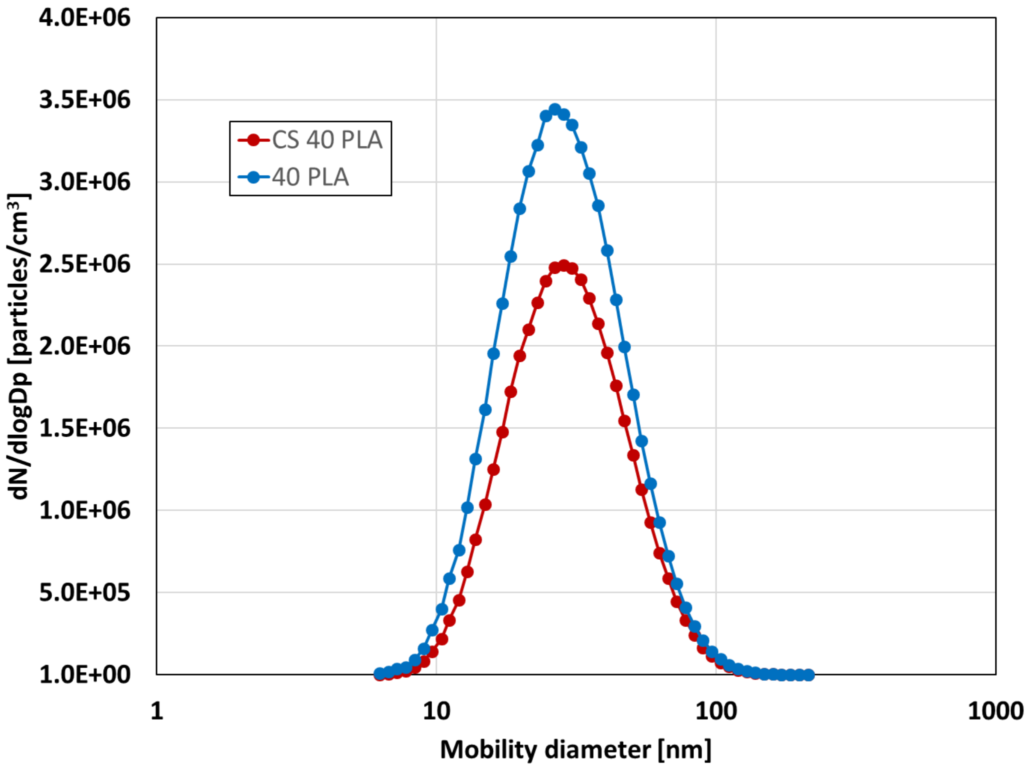


Size distributions – IGT-60 and J-85 with/without CS

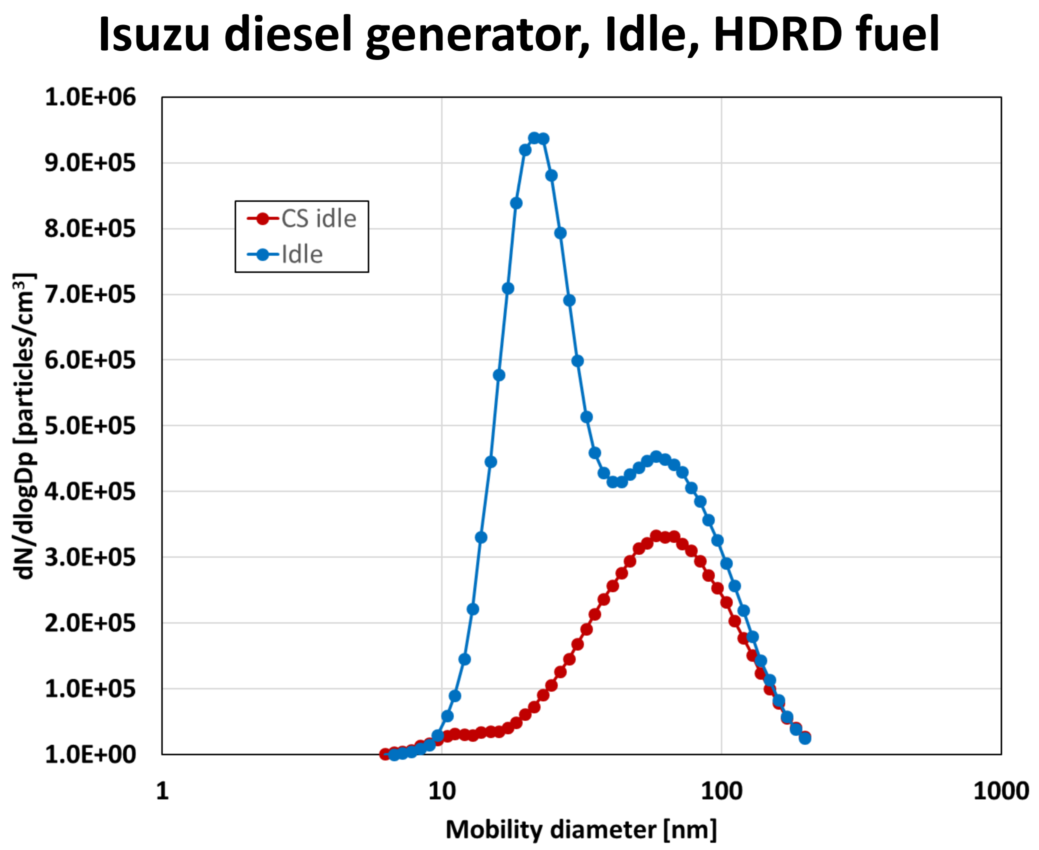
IGT-60 loaded (bleed air on)

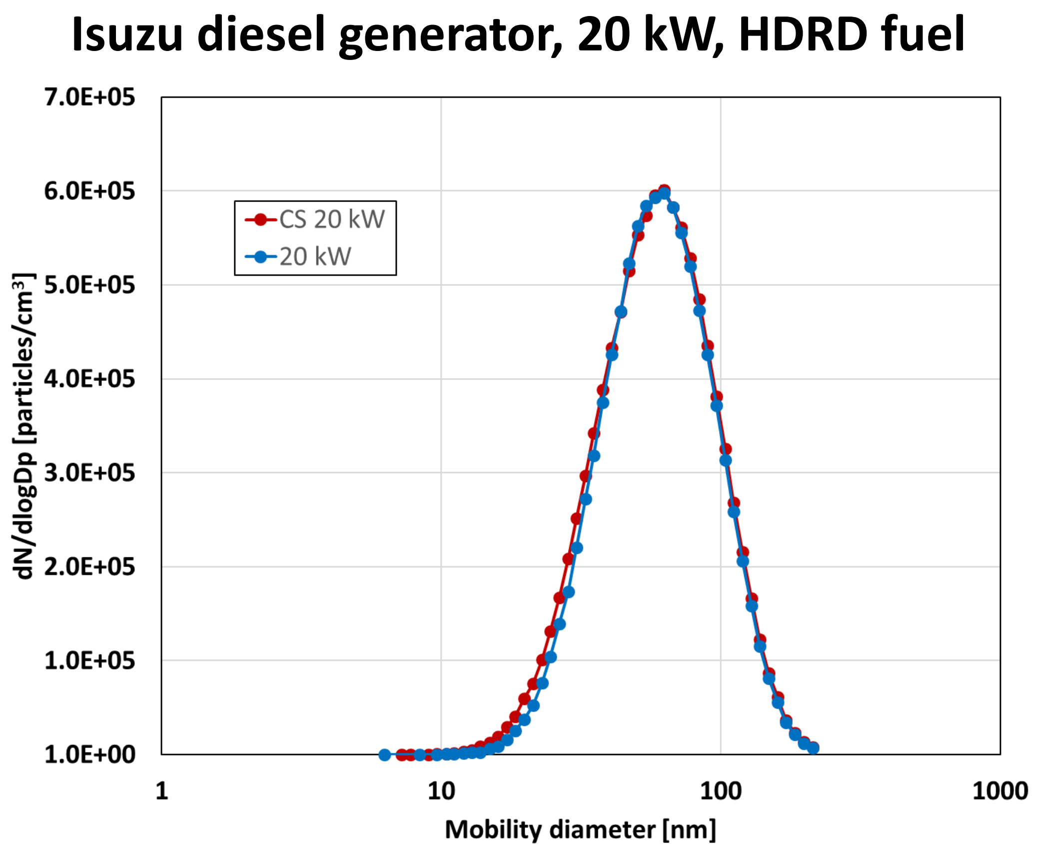


J-85 at medium thrust setting

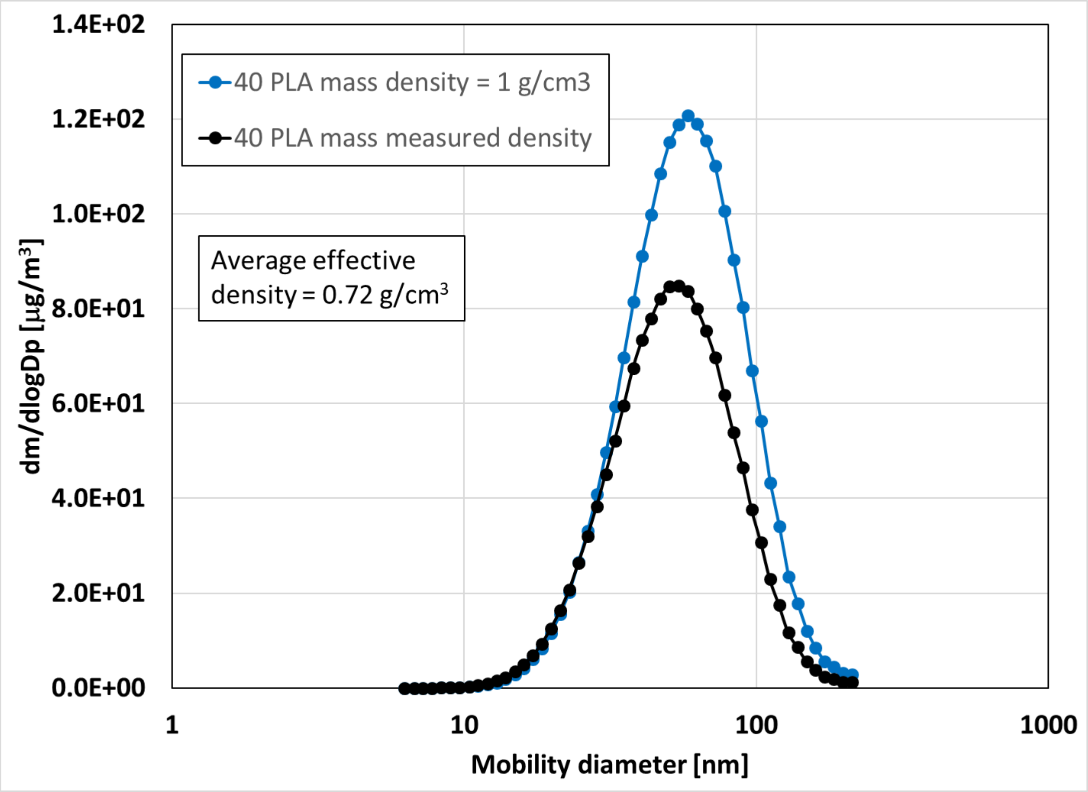


Size distributions – Isuzu Genset with/without CS





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

Summary

- Density shows inverse power law size dependence
  - Density proportional to Dp^{-n} where n ~ 0.3 to 0.4
  - This corresponds to a mass mobility relation, m proportional to $Dp^{(3-n)}$
- Up to 20% particle mass decrease association with removal of semivolatile material by the CS at 350 C
- Nonvolatile particle mass more dependent on load and fuel than total particle mass
- Accurate knowledge of density required for aircraft line loss correction. For the example case here incorrect density led to
  - 22% overestimate of line loss number correction
  - 6% overestimate of line loss mass correction

Questions

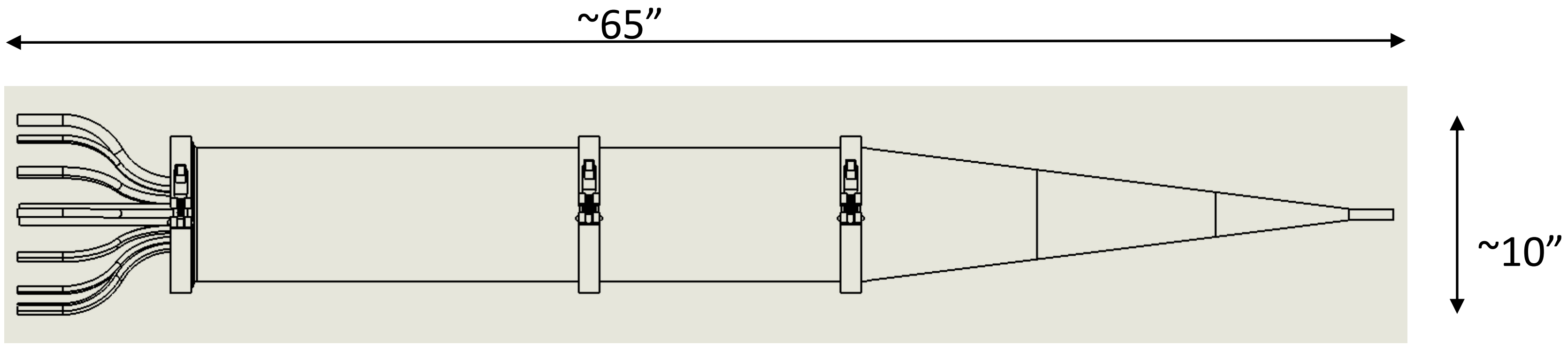
Supporting Information

Photos of AEDC Start Cart, J-85, and Diesel Engine Generator Set

ISUZU Diesel

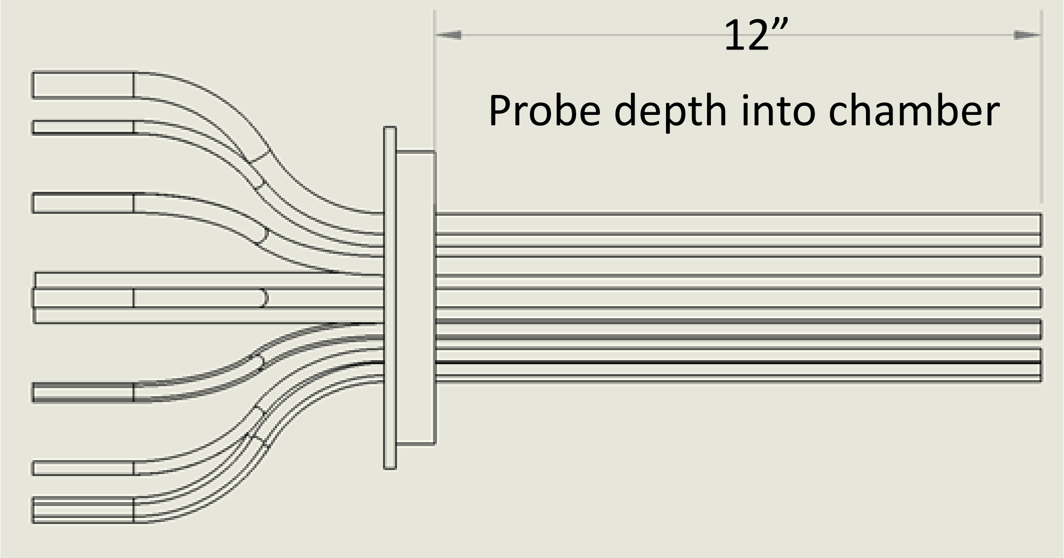
Sample Plenum Design

To instruments via 3/8" OD lines (Swagelok reducer/diffuser fittings when needed)

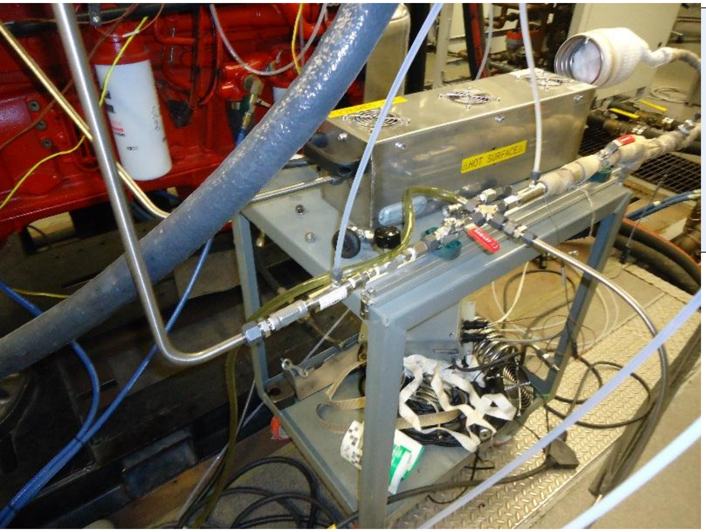


from front end

- Cone consists of 3 sections+1/2" inlet welded together
  - 2 sections purchased, 1 fabricated in AA
- Cone welded to ~1" quick clamp sanitary tubing
- Cone, 12", and 18" sections connected via clamp & gasket
- 18" section connected via clamp & gasket to end cap with probes
- Probe tubes of different diameters and assembly of end cap fabricated at NVFEL



Front End Sampling System for NVFEL



Heavy black lines indicate equipment wrapped in insulation