Aircraft PM: Estimating Size Dependant Sampling Losses without Measuring Size

Prof. David Kittelson
Center for Diesel Research
University of Minnesota

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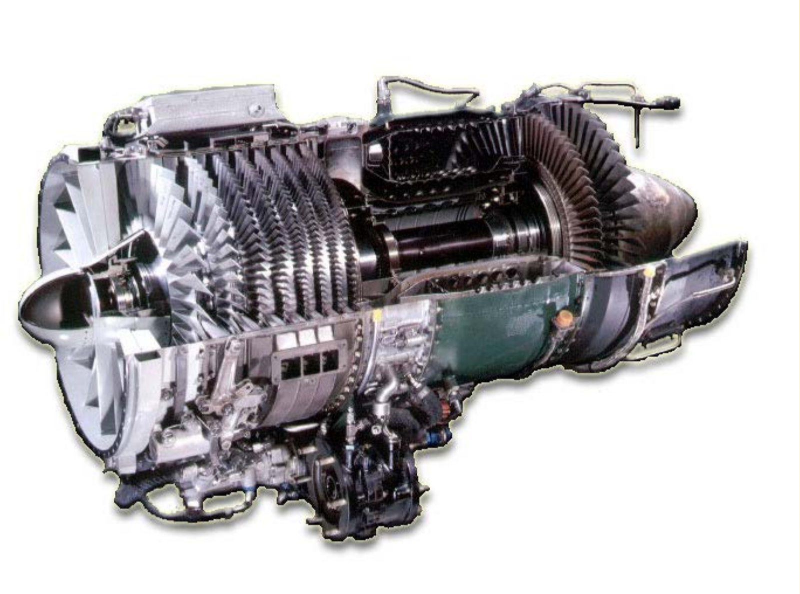
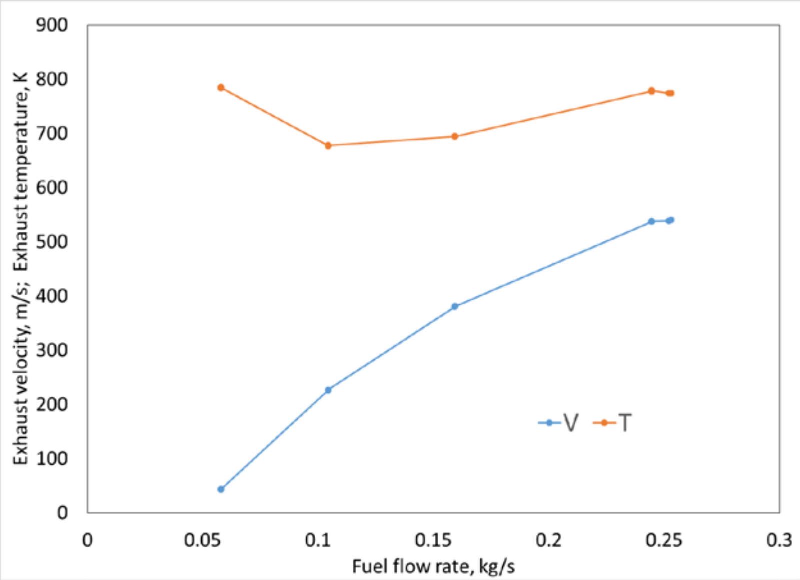
Department of Engineering
University of Cambridge
Trumpington Street
CB2 1PZ

Measuring particles from a J85 turbojet

Exhaust conditions more challenging than for piston engines

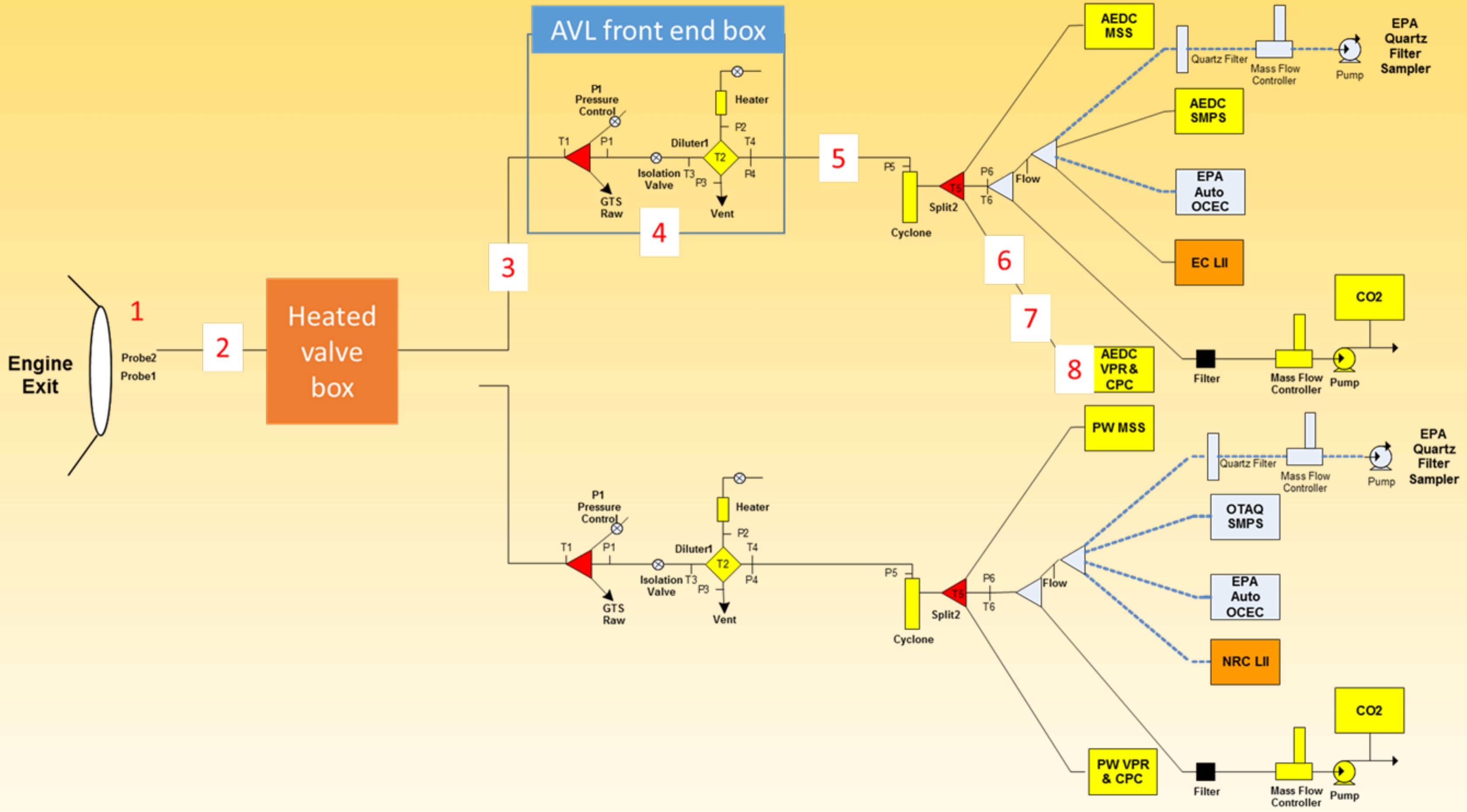




VAriable Response In Aircraft nvPM Testing (VARIAnT) Experiment

- Results here are a snapshot of some work done as a part of a larger study - VAriable Response In Aircraft nvPM Testing (VARIAnT) Experiment
- Its general objectives were evaluation of the source(s) of variability in the measurement of nvPM mass and number emitted by aircraft turbine engines
- Performed at University of Tennessee Space Science Institute
- I am focusing on the method for determining and correcting for sampling line losses
- Instruments used for work discussed today
  - AVL microsoot sensor (MSS) nvPM mass
  - AVL particle counter (APC) nvPN number
  - SMPS

Sampling system

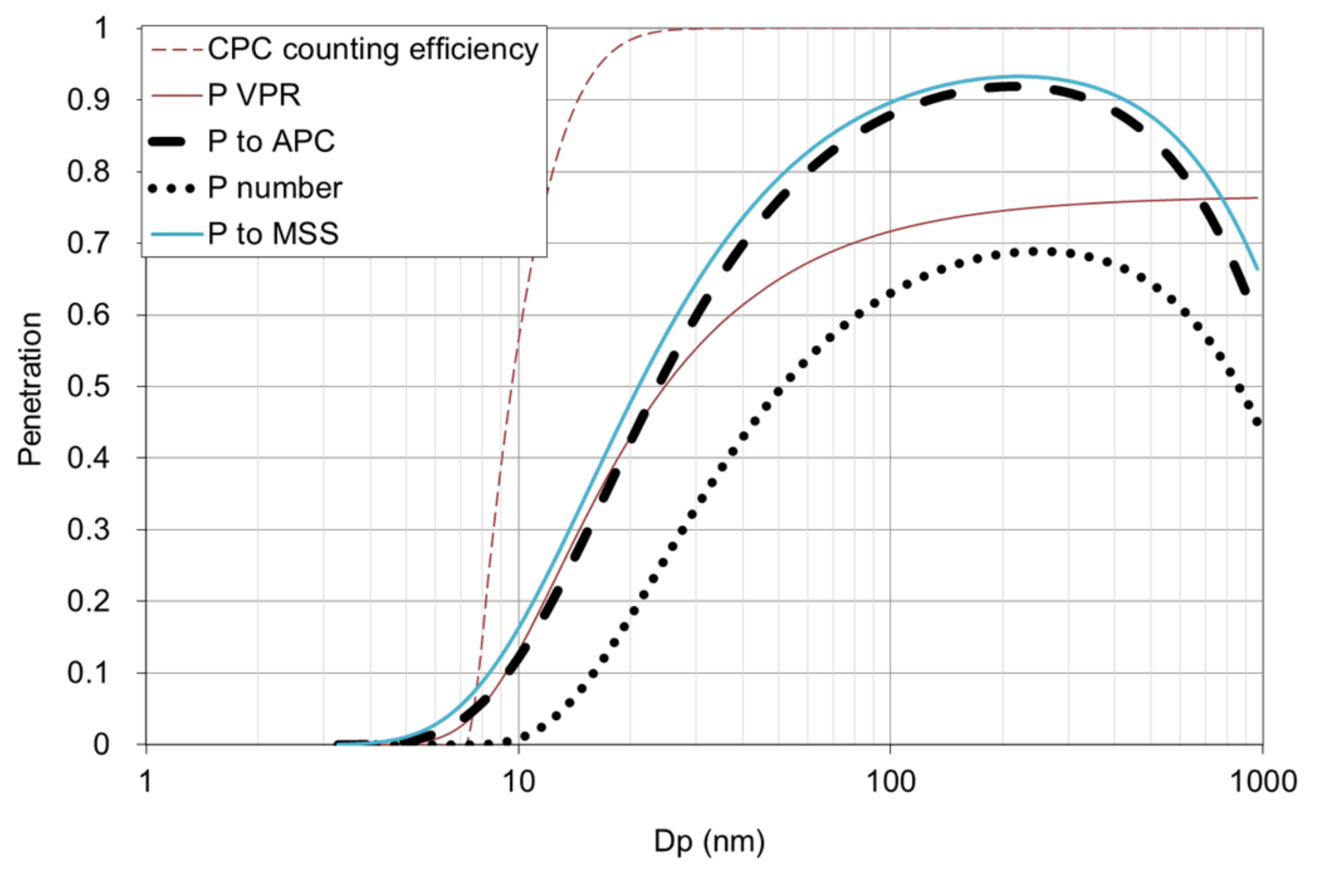


Sampling system geometry

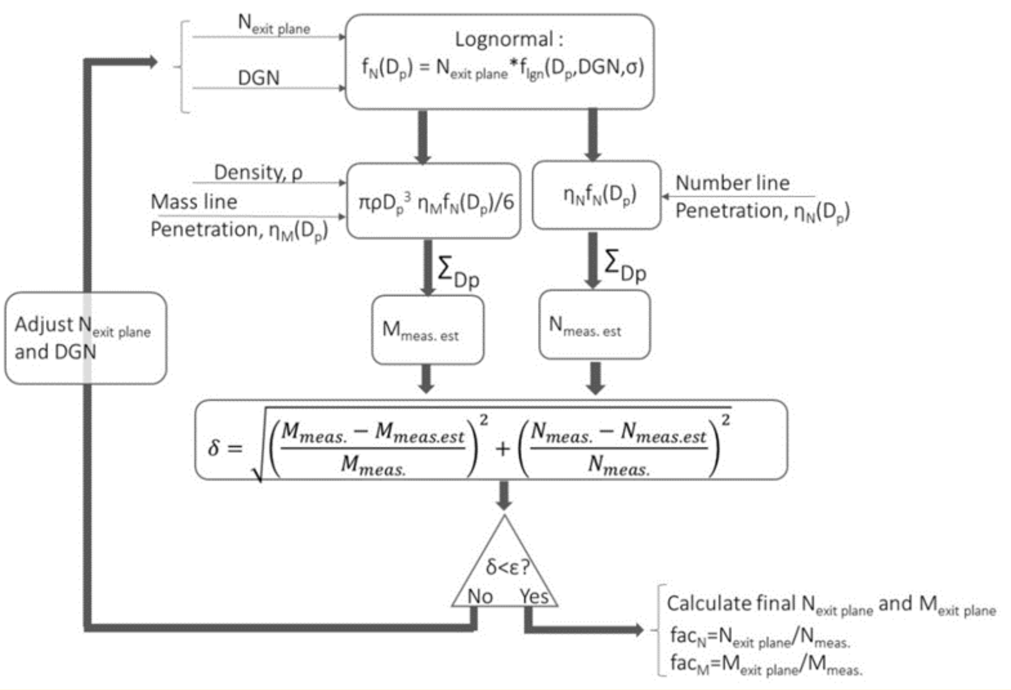
		red = inputs			values below used in transport calculation - they are automatically copied to the input sheet						
section		ID (inches)	Length (inches)	Bend (deg)	ID (cm)	Length (cm)	deg bends	Tg (K)	Tw (K)	Pg (atm)	flowrate (splm)
1	inlet	0.110	1	0	0.2794	2.5	0	774	774	1	64.8
2	to AEDC valve box	0.305	79	420	0.7747	200.7	420	905	800	1	64.8
3	to AVL front-end box	0.315	240	510	0.8001	609.6	510	800	433	1	64.8
4	front-end box	0.305	42	0	0.7747	106.7	0	433	433	1	5
5	25m line	0.305	984	1170	0.7747	2499.4	1170	333	333	1	25
6	to APC diluter	0.157	67	250	0.4000	170.2	250	333	333	1	5
7	APC diluter	0.157	6.25	0	0.4000	15.9	0	333	333	1	5
8	to APC	0.157	81.5	525	0.4000	207.0	525	333	303	1	5
6a*	25 m line to MSS	0.157	53	230	0.4000	134.6	230	333	303	1	5
					Line lengths	9.2	m				
						28.9	m				

Sections 1-4 undiluted, 10:1 dilution between 3 and 4

Long sampling lines lead to large wall losses, especially for small particles

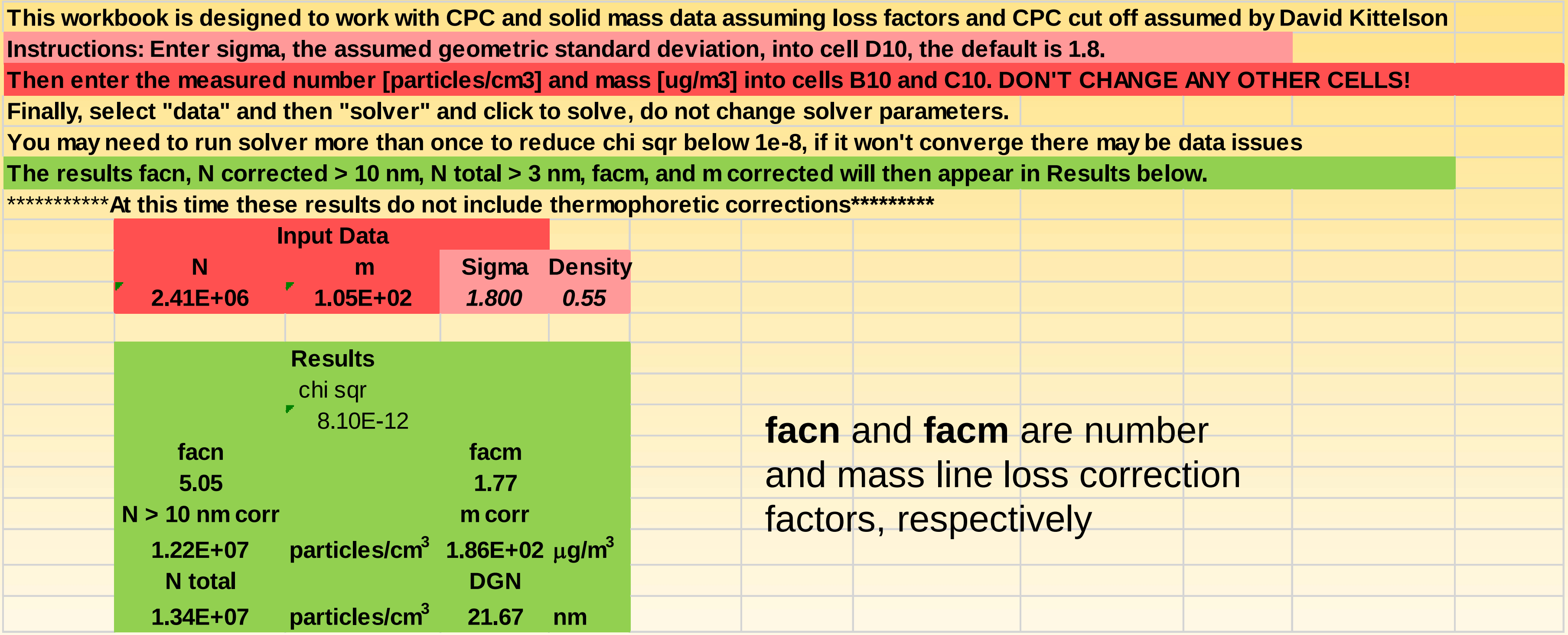


Line loss correction method



- Only measurements available are nvPM and nvPN
- Requires well validated line loss model, currently uses UTRC model
- Assumptions
  - no nucleation or coagulation
  - engine exit plane size distribution is log normal
  - 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, after line losses yields the observed nvPM and nvPN
- Method based on concept originally developed by Don Hagen (MS&T)

Line loss data entry and solution page



This workbook is designed to work with CPC and solid mass data assuming loss factors and CPC cut off assumed by David Kittelson

Instructions: Enter sigma, the assumed geometric standard deviation, into cell D10, the default is 1.8.

Then enter the measured number [particles/cm3] and mass [ug/m3] into cells B10 and C10. DON'T CHANGE ANY OTHER CELLS!

Finally, select "data" and then "solver" and click to solve, do not change solver parameters.

You may need to run solver more than once to reduce chi sqr below 1e-8, if it won't converge there may be data issues

The results facn, N corrected > 10 nm, N total > 3 nm, facm, and m corrected will then appear in Results below.

***********At this time these results do not include thermophoretic corrections*********

Input Data

N	m	Sigma	Density
2.41E+06	1.05E+02	*1.800*	*0.55*

Results

chi sqr

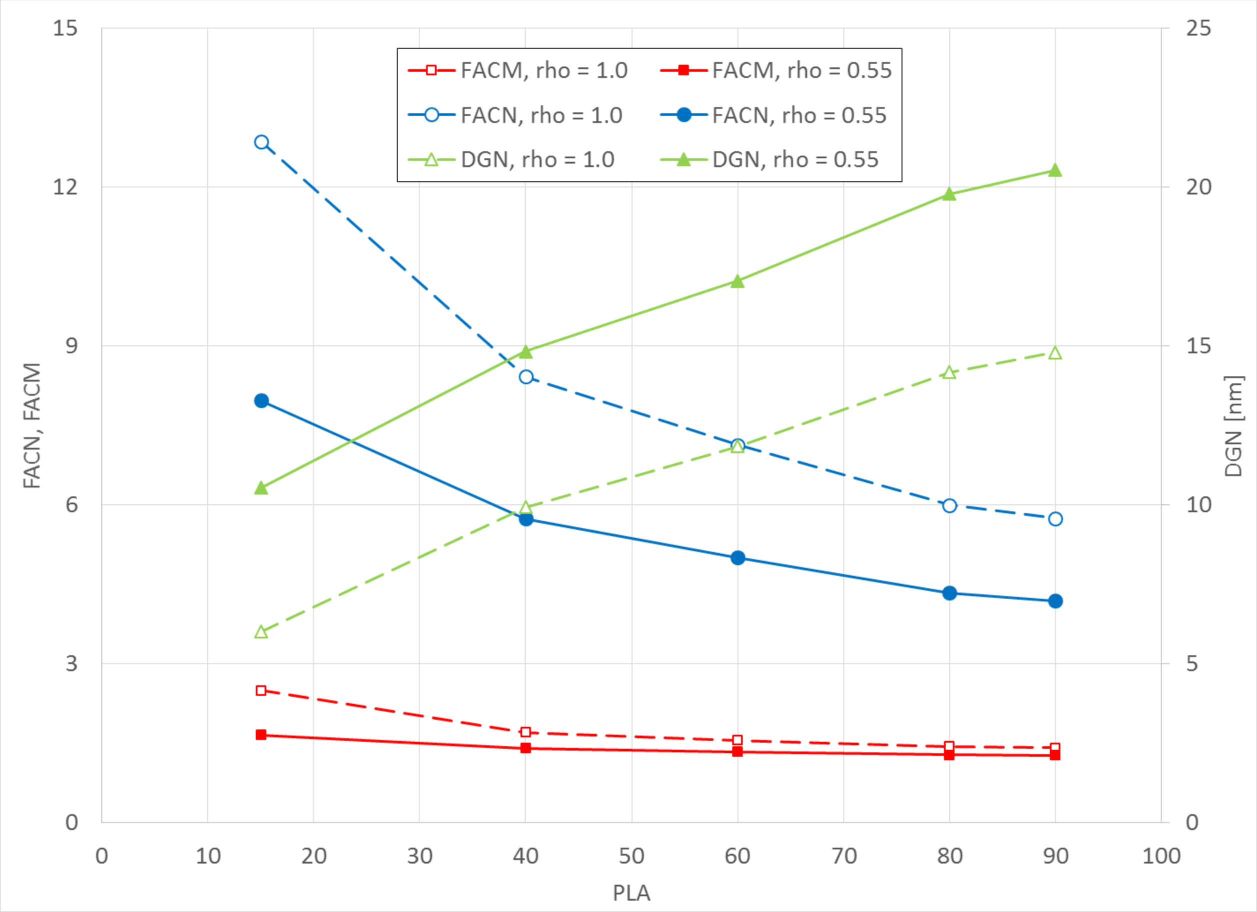
8.10E-12

facn		facm	
5.05		1.77	
N > 10 nm corr		m corr	
1.22E+07	particles/cm^3	1.86E+02	µg/m^3
N total		DGN	
1.34E+07	particles/cm^3	21.67	nm

facn and **facm** are number and mass line loss correction factors, respectively

Line loss corrections and calculated exit plane diameters VARIAnT data, Jet A fuel

PLA is power lever angle increasing thrust from PLA 15 to PLA 90

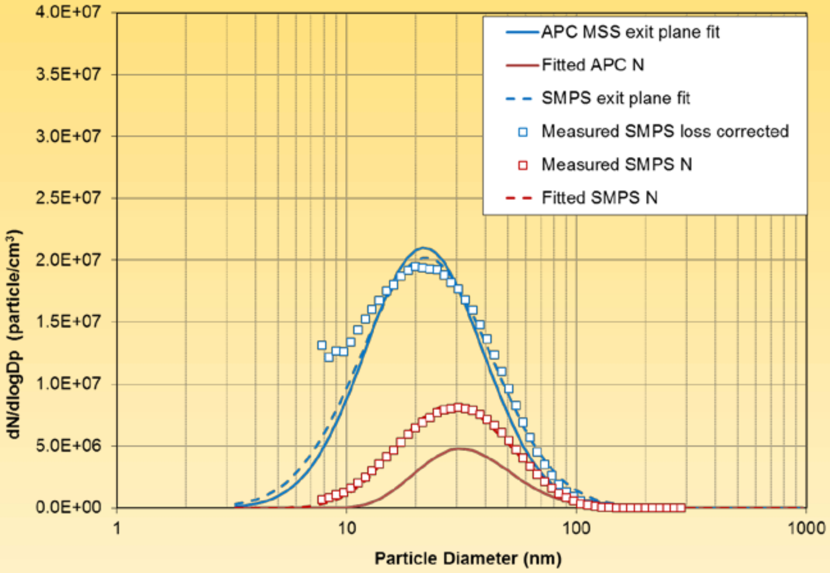


SMPS based loss corrections

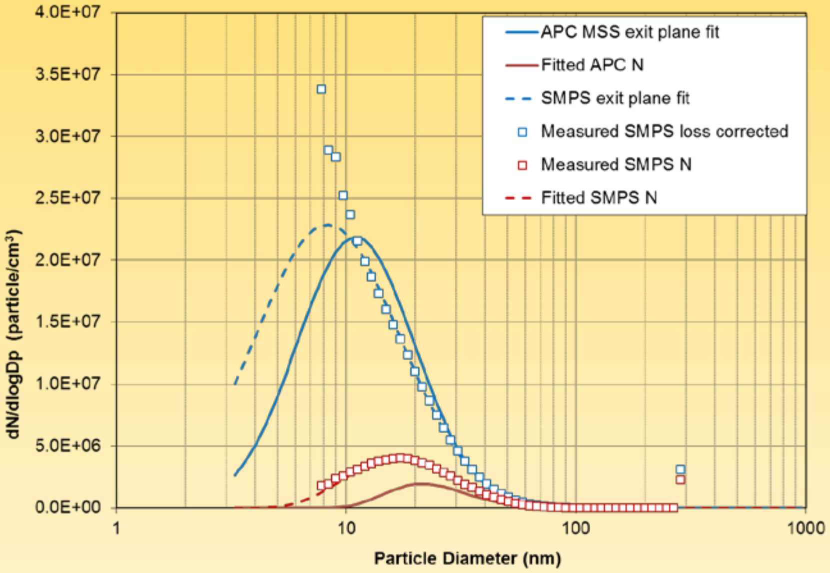
- For this study, SMPS data were also collected
- These data were used in two ways
  - Measured channel by channel size data were corrected to exit plane values by dividing by line loss transfer function to yield an exit plane size distribution
  - An exit plane log normal distribution was assumed and its properties, N, σ_g, and DGN were varied to minimize the squared error between the measured and calculated size distribution
- Comparison of these result and the results of the inversion process based on nvPN and nvPM alone allow uncertainties to be explored

Exit plane size distributions using nvPN and nvPM method compared to SMPS method

Maximum thrust PLA 90



Minimum thrust PLA 15

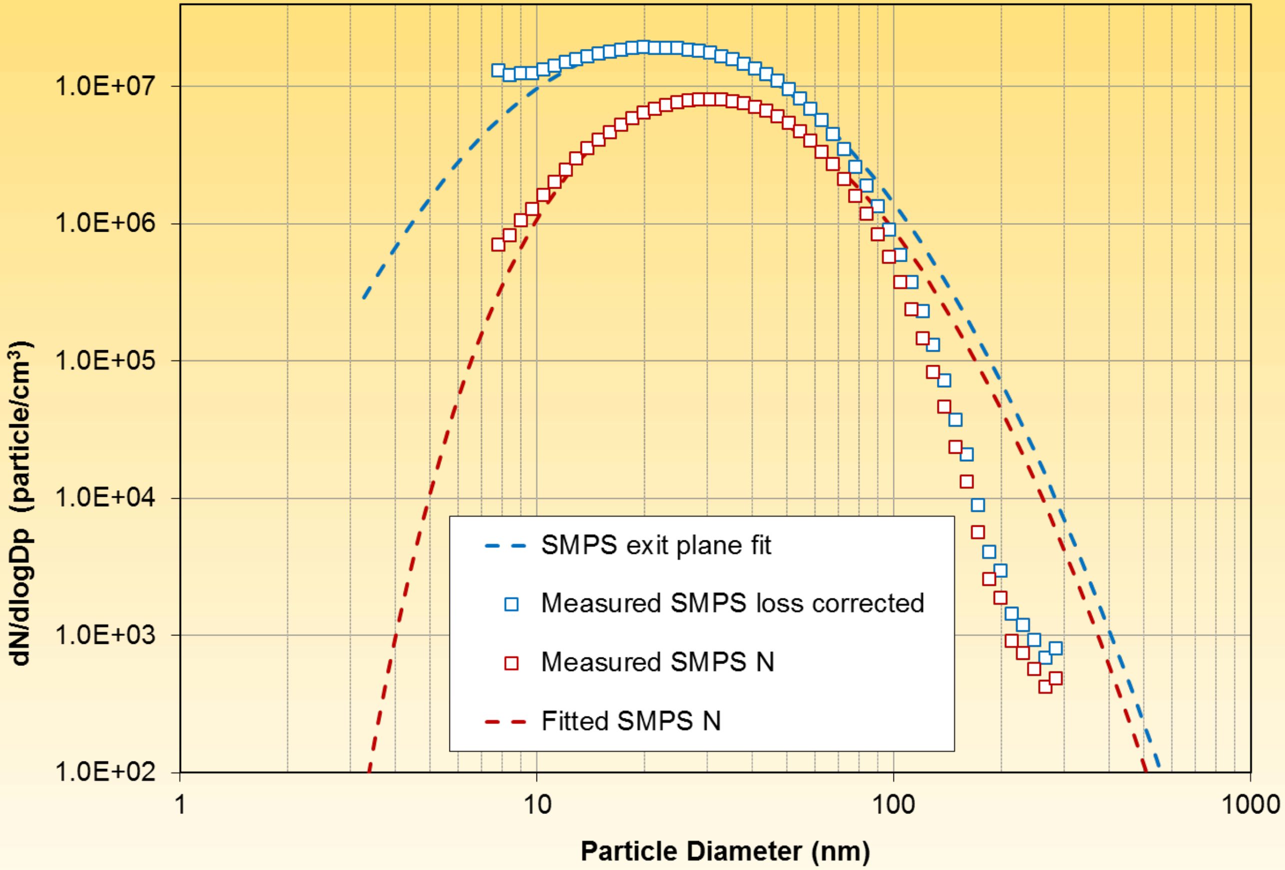


	PLA 90 100% thrust		PLA 15 ~ 7% thrust	
	MSS and APC	SMPS	MSS and APC	SMPS
density, g/cm^3	0.55		0.55	
Sigma g	1.8	1.92	1.8	2.06
DGN, nm	21.7	22.1	11	8.3
N exit part./cm^3	1.22E+08	1.28E+08	7.89E+07	7.15E+07
m exit, μg/m^3	1860		253	
facn	1.77		9.42	
facm	5.05		2.11	

Issues with line loss correction method

- Gives reasonable results over range of conditions, but..
- Uncertainties
  - Variations in σ_g
  - Density that gives reasonable results inconsistent with direct density measurements
  - Line losses
  - Inversion based on nvPM and nvPN, actual exit plane includes volatiles
  - Departures from log-normal at exit plane
  - Nucleation and coagulation

Departures from lognormal, Jet A, maximum thrust (PLA = 90)



Coagulation: assessing its importance, a simplified approach

- The line loss correction is first order but coagulation is second. When particle size does not change much, simple expressions may be used

$$\frac{dN}{dt} = -kN^2 \qquad \frac{N}{N_0} = \frac{1}{1 + kN_0\tau}$$

where k is the average coagulation coefficient, N is number, and τ is time

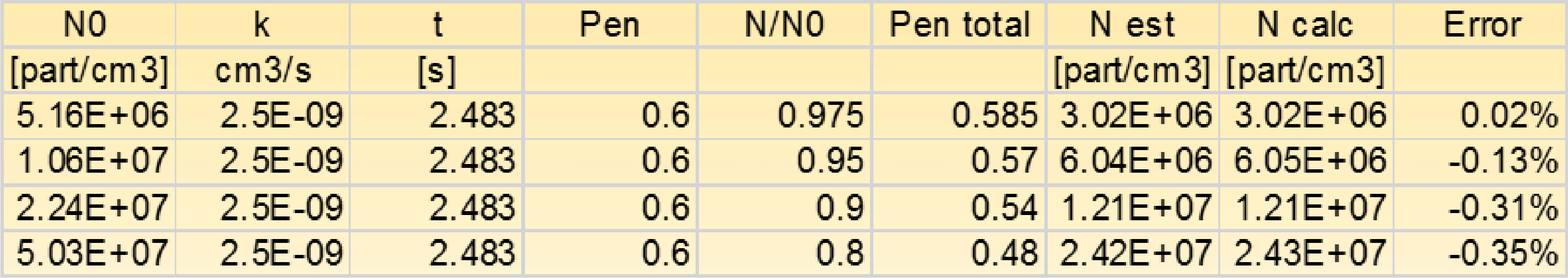
- In the sampling line N is reduced by changes by both wall loss and coagulation To combine these losses we use average N based on wall loss in that line section leading to

$$\frac{N}{N_0} = \frac{1}{1 + kN_{av}\tau} \qquad N_{av} = N_0\left(\frac{1+P}{2}\right)$$

where P is penetration based on wall loss only

Coagulation – validity of separate treatment of coagulation and wall loss

- How accurate is treating coagulation and wall loss separately and then combining?
- Here we compare results of a Runge-Kutta solution of combined coagulation and wall loss with the simple model described above.

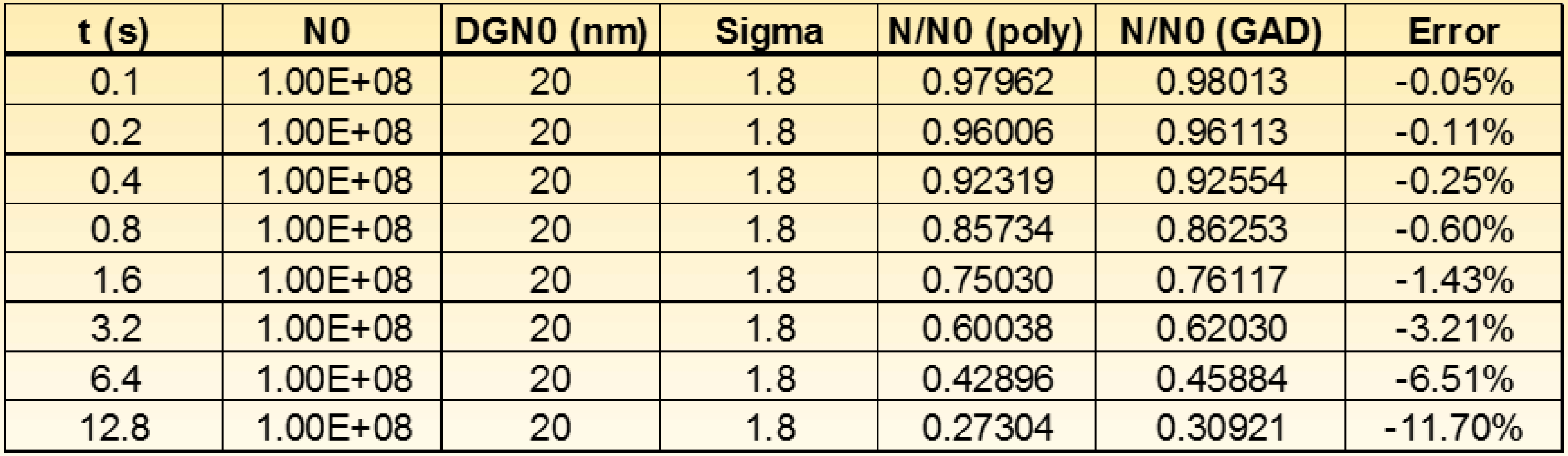


N0	k	t	Pen	N/N0	Pen total	N est	N calc	Error
[part/cm3]	cm3/s	[s]				[part/cm3]	[part/cm3]	
5.16E+06	2.5E-09	2.483	0.6	0.975	0.585	3.02E+06	3.02E+06	0.02%
1.06E+07	2.5E-09	2.483	0.6	0.95	0.57	6.04E+06	6.05E+06	-0.13%
2.24E+07	2.5E-09	2.483	0.6	0.9	0.54	1.21E+07	1.21E+07	-0.31%
5.03E+07	2.5E-09	2.483	0.6	0.8	0.48	2.42E+07	2.43E+07	-0.35%

- N/N_0 never goes below 0.9 in any line section so errors are small

Coagulation – validity of assuming a constant coagulation coefficient in each line section

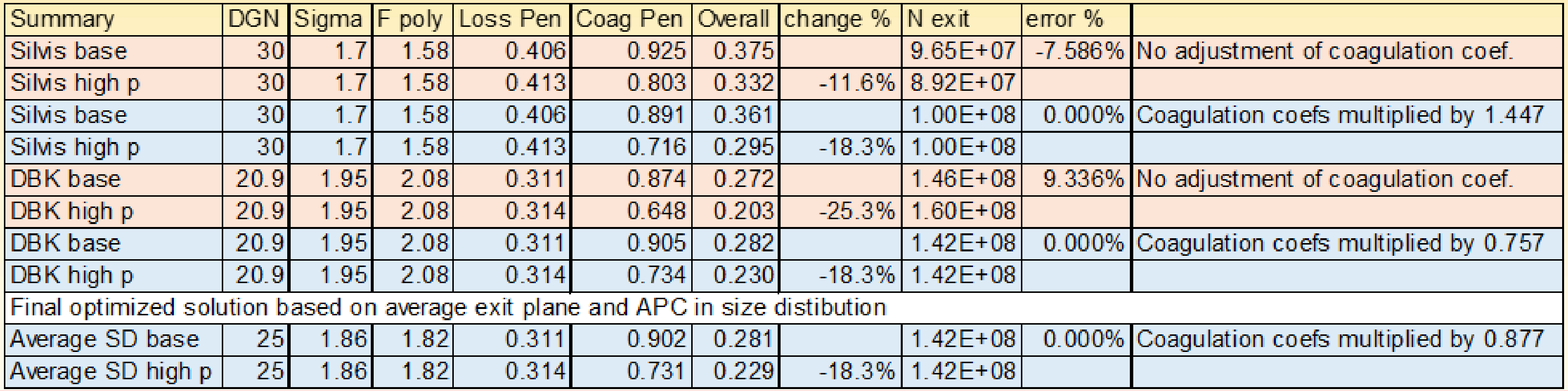
- How accurate is assuming a constant coagulation coefficient and monodisperse coagulation?
- Here we the solution of general aerosol dynamics equation and simple constant k coagulation
- Errors are less than 2% for $N/N_0 > 0.75$
- N/N_0 never goes below 0.9 in any line section



t (s)	N0	DGN0 (nm)	Sigma	N/N0 (poly)	N/N0 (GAD)	Error
0.1	1.00E+08	20	1.8	0.97962	0.98013	-0.05%
0.2	1.00E+08	20	1.8	0.96006	0.96113	-0.11%
0.4	1.00E+08	20	1.8	0.92319	0.92554	-0.25%
0.8	1.00E+08	20	1.8	0.85734	0.86253	-0.60%
1.6	1.00E+08	20	1.8	0.75030	0.76117	-1.43%
3.2	1.00E+08	20	1.8	0.60038	0.62030	-3.21%
6.4	1.00E+08	20	1.8	0.42896	0.45884	-6.51%
12.8	1.00E+08	20	1.8	0.27304	0.30921	-11.70%

Is coagulation important for typical engine and sampling conditions?

- Jet A, PLA 90 (100% thrust), highest emission case tested
- Natural experiment, restricting dump flow raised pressure ahead of ejector increasing coagulation due to
  - Higher N before dilution due to p
  - Longer residence time
  - Decreased dilution and higher N in 25 m line
- Coagulation coefficient depends on T, p, DGN and σ_g
  - Assuming upstream size distribution underestimate loss
  - Assuming downstream size distribution overestimates
  - Simple average comes close
- Using these adjusted coefficients predicts 10% coagulation loss for normal sampling conditions
- Old engine, high load, likely worst case



Summary	DGN	Sigma	F poly	Loss Pen	Coag Pen	Overall	change %	N exit	error %	
Silvis base	30	1.7	1.58	0.406	0.925	0.375		9.65E+07	-7.586%	No adjustment of coagulation coef.
Silvis high p	30	1.7	1.58	0.413	0.803	0.332	-11.6%	8.92E+07		
Silvis base	30	1.7	1.58	0.406	0.891	0.361		1.00E+08	0.000%	Coagulation coefs multiplied by 1.447
Silvis high p	30	1.7	1.58	0.413	0.716	0.295	-18.3%	1.00E+08		
DBK base	20.9	1.95	2.08	0.311	0.874	0.272		1.46E+08	9.336%	No adjustment of coagulation coef.
DBK high p	20.9	1.95	2.08	0.314	0.648	0.203	-25.3%	1.60E+08		
DBK base	20.9	1.95	2.08	0.311	0.905	0.282		1.42E+08	0.000%	Coagulation coefs multiplied by 0.757
DBK high p	20.9	1.95	2.08	0.314	0.734	0.230	-18.3%	1.42E+08		
Final optimized solution based on average exit plane and APC in size distibution										
Average SD base	25	1.86	1.82	0.311	0.902	0.281		1.42E+08	0.000%	Coagulation coefs multiplied by 0.877
Average SD high p	25	1.86	1.82	0.314	0.731	0.229	-18.3%	1.42E+08		

Going forward

- New regulations on nvPM and nvPN are being established
  - Engine companies are characterizing engines and reporting
  - Levels will be agreed by 2020
- Long sampling line require very large corrections for line losses
  - May exceed 9x for number, 2x for mass
  - Losses are size dependent but engine companies only want to measure number and mass
  - Validity of assumptions still under question
  - Measurements of size or another metric, e.g., surface would reduce uncertainty
- Possible future issue
  - nvPM based on instruments that measure black carbon (BC), proportional to elemental carbon (EC)
  - With very clean combustion systems
    - Relationship between BC and EC may change
    - Lube oil ash may play a larger role
  - nvPN detects all non-volatile particles, carbon, ash,…

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