Hagen_ETH2011_Jet Exhaust Mean Size_Summary

A new Aerospace Recommended Practices protocol is being developed for jet engine exhaust emissions measurement. Regulation agencies have indicated that the aerosol parameters that need to be measured are non-volatile soot number and mass concentrations. No direct particle size measurements are required. However size information is needed for relating the measured number and mass at the downstream end of the sampling train to values at the engine exit plane. A reasonable estimate for the exhaust aerosol's non-volatile mean size, at the end of a 25m sample train, can be generated from the required number and mass concentrations. The method exploits a correlation between the soot's geometric mean diameter and the size distribution's geometric standard deviation that has been observed during four jet engine emission test campaigns.

An uncertainty analysis is presented which can be used to estimate the impact of a number counting cut-size on engine exit plane number concentration uncertainty. For soot GMDs near the small end of the range observed in numerous engine test campaigns, the optimum cut size is between 10 and 11 nm for exhaust containing a volatile mode in the range from 7 to 9 nm. The optimization minimizes the uncertainty in the engine exit plane number concentration determination.

PARTNER

Partnership for AiR Transportation Noise and Emission Reduction

An FAA/NASA/TC-sponsored Center of Excellence

Mean Sizes for Gas Turbine Exhaust Soot Sampled at Engine Exit Plane

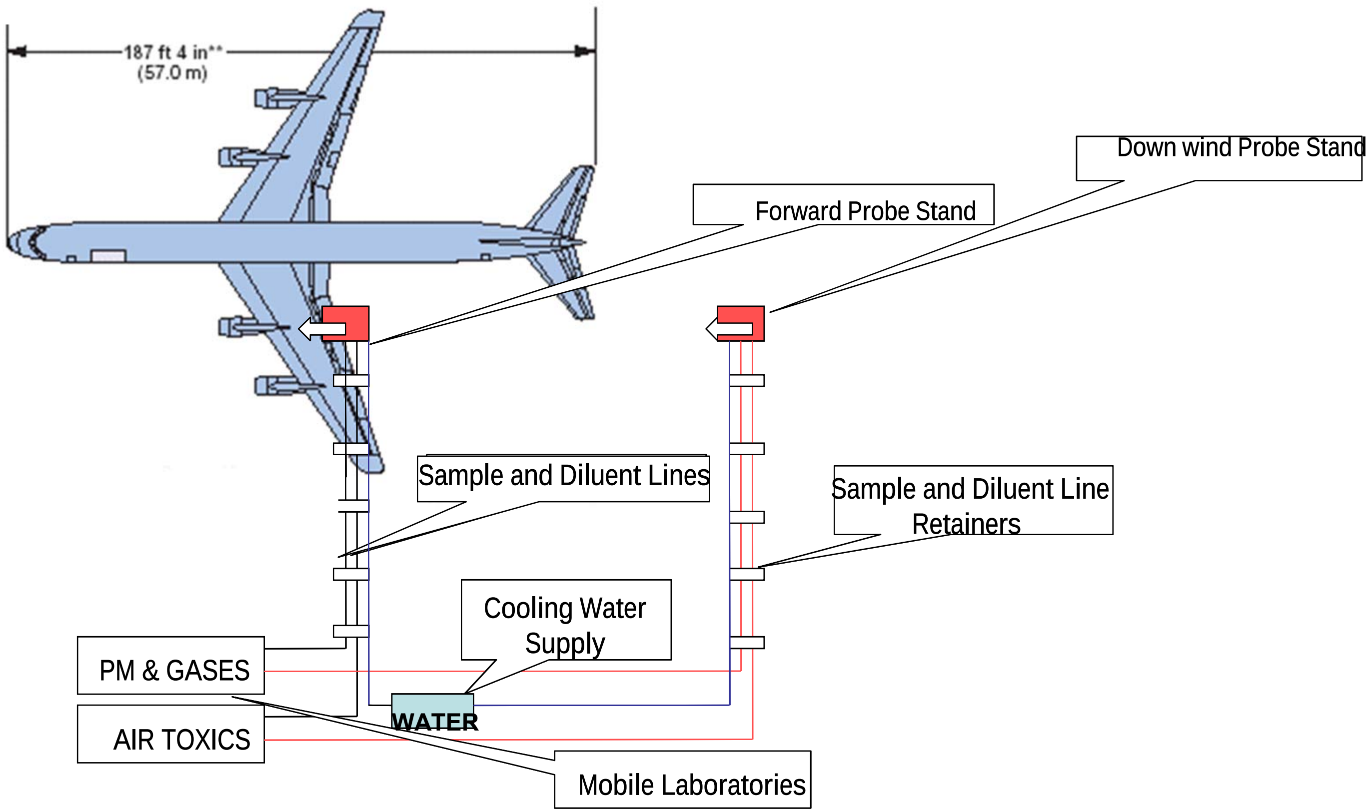
D. Hagen, P. Whitefield , and P. Lobo
Missouri Univ. of Sci. & Techn.

15th ETH Conference on Combustion Generated Nanoparticles
Zurich
June 2011

Determine GMD from measured N and M concentrations

- APEX 1, April 2004, NASA Dryden
- Delta ATL, Sept 2004, Atlanta Hartsfield
- Jets APEX 2, Aug 2005, Oakland CA
- AAFEX 1, Jan 2009, Palmdale CA

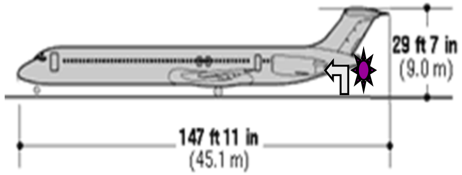
McDonnell Doublas DC-8 with CFM 56-2C1 engines



Configuration Of Sampling Equipment During Aircraft Testing In Project APEX

Delta ATL: Airframe / engine combinations tested

DATE	AIRFRAME	ENGINE
21 Sept 2004	MD-88	JT8D-219
22 Sept 2004	MD-88	JT8D-219
	B767-300	CF680C2
23 Sept 2004	B767-400	CF680C2B8F
	B757-200	PW2037
24 Sept 2004	B757-200	PW2037

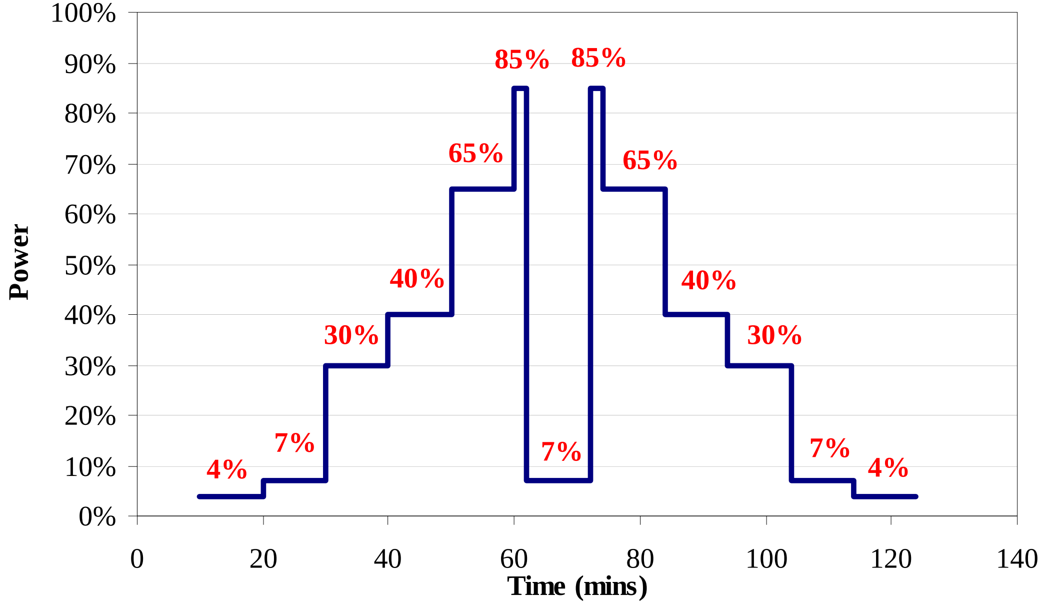


Extractive Sampling Characterization:

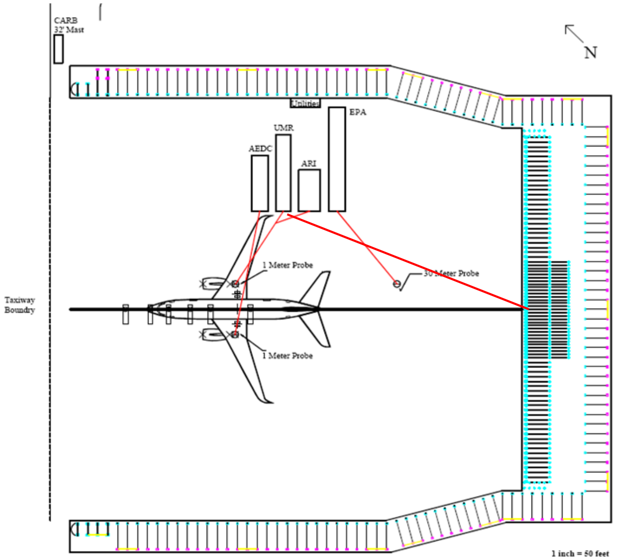
Particle count, size, size distribution, soluble mass fraction, particle composition, and black carbon mass were measured at the vans. CO2 was also measured to reference the particle emissions quantities to the rate of fuel burned.

Jets APEX 2 Overview

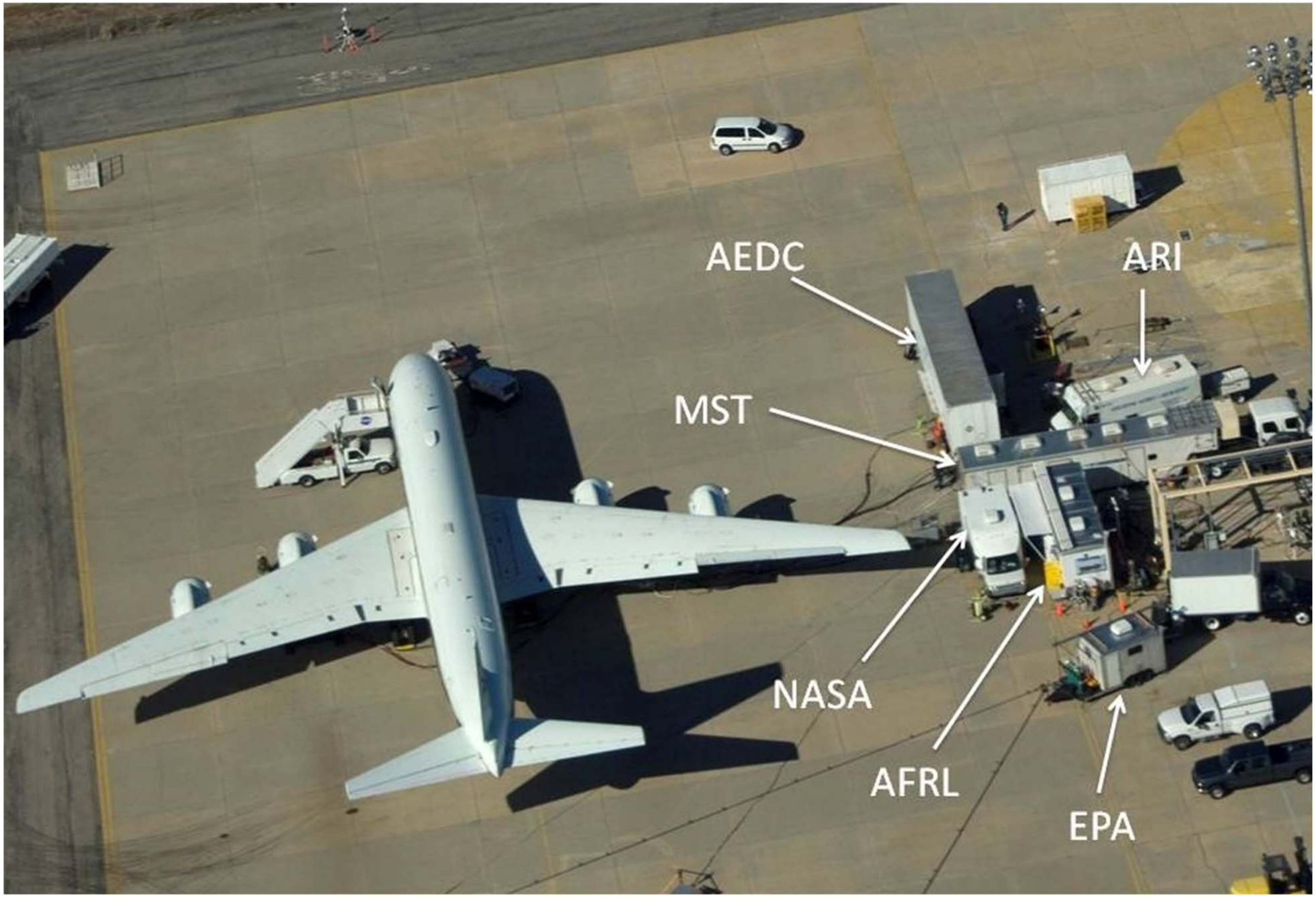
Date	Aircraft Tail No	Airframe	Engine
August 23, 2005	N435WN	B737-700	CFM56-7B22
August 24, 2005	N353SW	B737-300	CFM56-3B1
August 24, 2005	N695SW	B737-300	CFM56-3B1
August 25, 2005	N429WN	B737-700	CFM56-7B22



Jets APEX 2: Oakland GRE

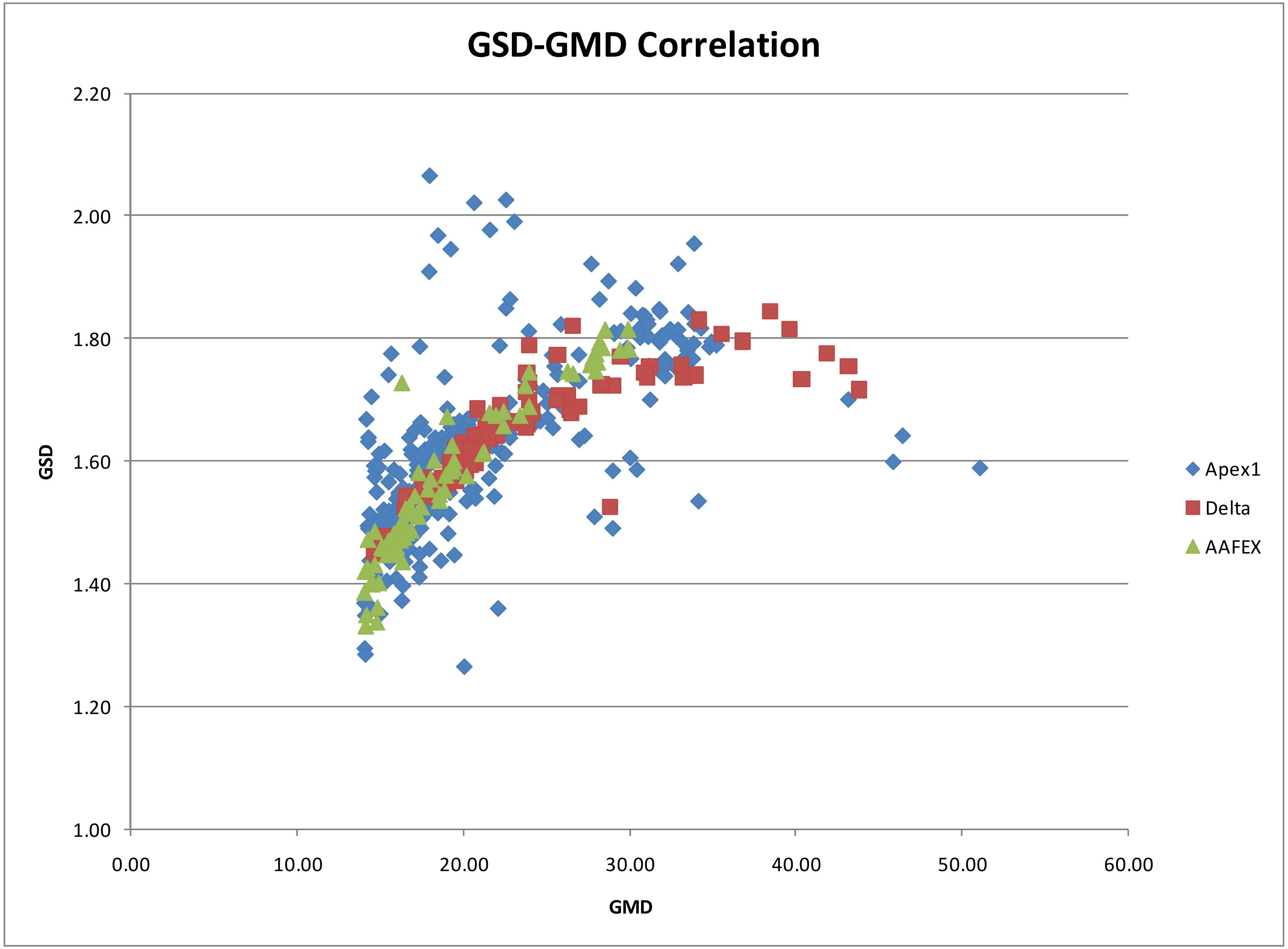


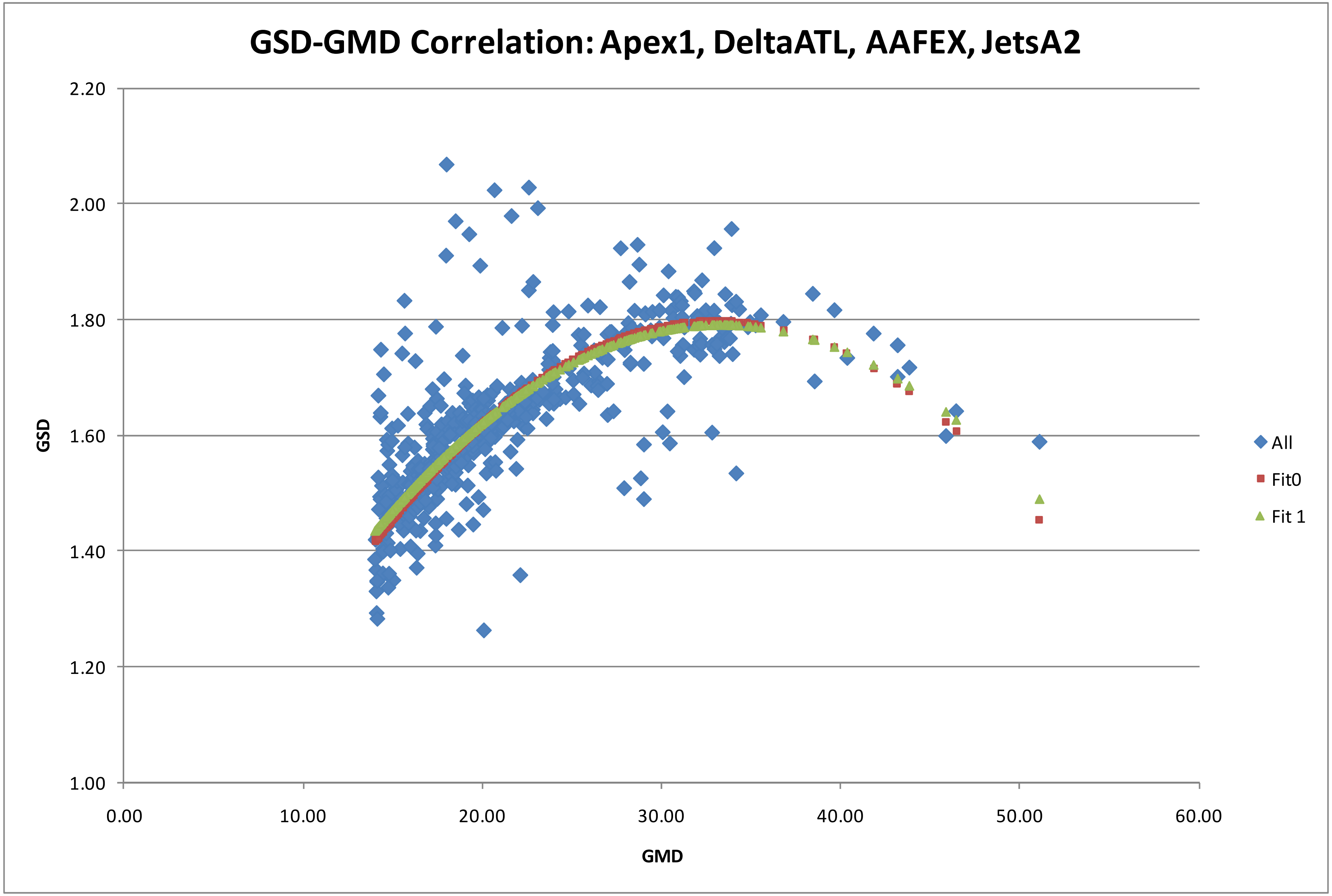
AAFEX Jan 2009, Palmdale CA



Method

- Exhaust aerosols are typically lognormal.
- $\frac{dN}{dlogx} = \frac{N}{\sqrt{2\pi}\,S} e^{-(logx - logGMD)^2/(2S^2)}$
  - S = log(GSD)
  - s = ln(GSD)
  - Parameters: N, GMD, GSD
- Mass concentration
  - $M = \left(\frac{\pi}{6}\right)\rho \frac{N}{\sqrt{2\pi}\,s} \int_0^\infty \left(\frac{dx}{x}\right) x^3 e^{-(lnx - G)^2/(2s^2)}$
  - $M = \left(\frac{\pi}{6}\right)\rho N * GMD^3 * \exp(4.5s^2)$
- $X = \left(\frac{6M}{\pi\rho N}\right)^{1/3} = GMD * \exp(1.5s^2)$
- If you know s(GMD), then meas N & M, calc X, solve for GMD.


GSD-GMD Correlation
2.20
2.00
1.80
1.60
1.40
1.20
1.00
GSD
0.00
10.00
20.00
30.00
40.00
50.00
60.00
GMD
Apex1
Delta
AAFEX


GSD-GMD Correlation: Apex1, DeltaATL, AAFEX, JetsA2
2.20
2.00
1.80
1.60
1.40
1.20
1.00
GSD
0.00
10.00
20.00
30.00
40.00
50.00
60.00
GMD
All
Fit0
Fit 1

GSD as function of GMD

- RMS δGSD/GSD = 4.2%
- GSD = -0.0009563*GMD^2 + 6.373E-02*GMD + 0.7287
- s = ln(GSD)
- X(N,M) = GMD*exp(1.5s^2)
- Invert this to get GMD(X)
- GMD = 1.7875E-04*X^3 – 0.018795*X^2 + 1.0976*X – 0.020442
- $X = \left(\frac{6M}{\pi \rho N}\right)^{1/3}$

Application

- Select a lower size cutoff jet exhaust measurement
  - Soot mode
  - Volatile mode
- Minimize uncertainty in number measurement at probe tip

Five error contributions to N_{pr}

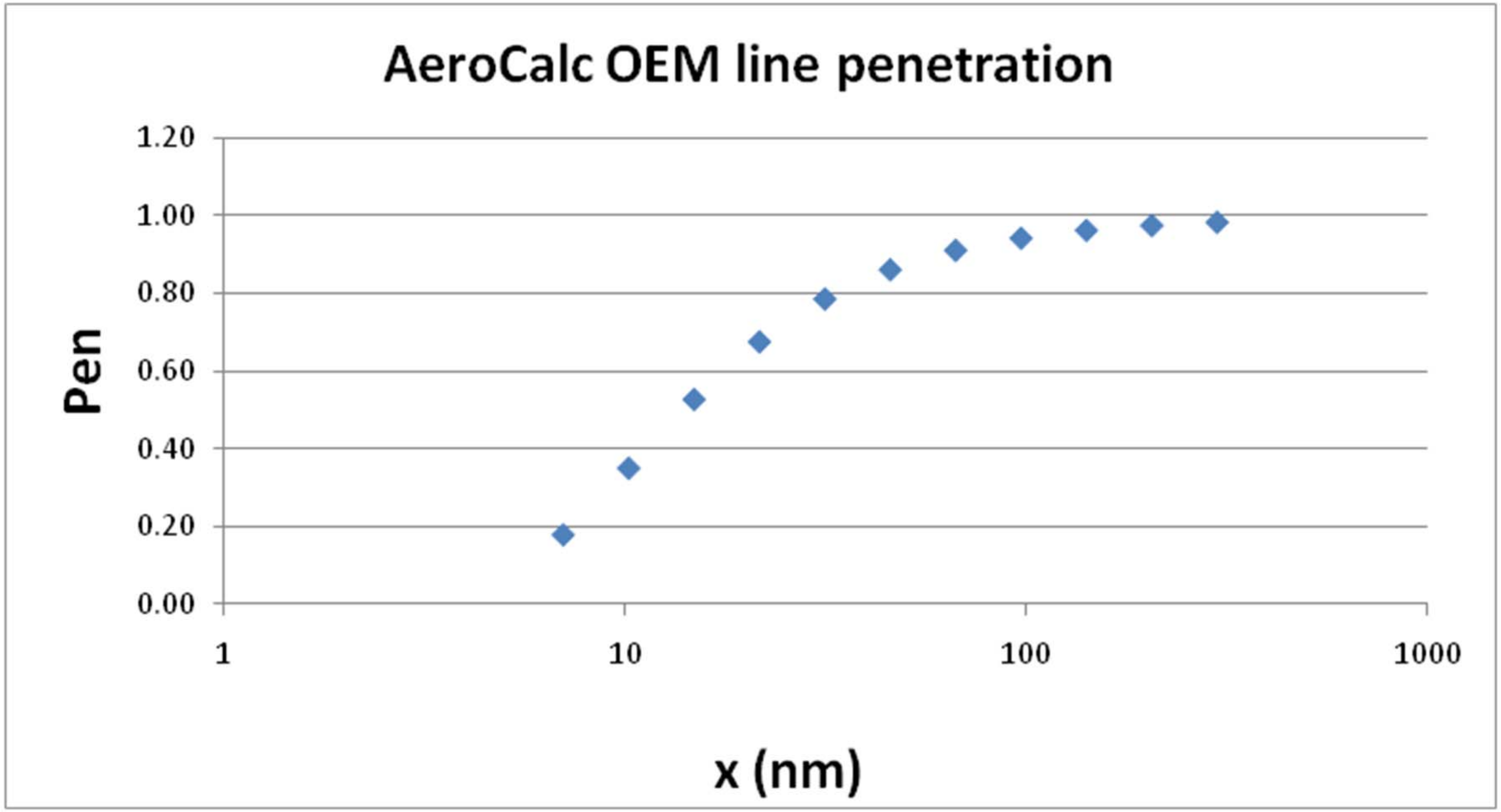
- $N_{pr} = N_{instr}/pen(GMD)$
- Uncertainties in numerator
  - Normal instr error for number δN/N = 0.20
  - Cut-off non-volatile $\left(\frac{1}{N}\right)\int_0^{xc}\left(\frac{dN}{dx}\right)dx = \frac{1}{2}\operatorname{erfc}\left(\frac{G-yc}{\sqrt{2}\,s}\right)$
    yc = ln(xc)
  - Volatile mode $N'c = \int_{xc}^{\infty}\left(\frac{dN'}{dx}\right)dx = \frac{N'}{\sqrt{2\pi}\,s'}\int_{xc}^{\infty}\left(\frac{dx}{x}\right)e^{-(\ln x-G')^2/(2s'^2)}$

$$N'fc = \frac{N'c}{N} = \left(\frac{N'}{2N}\right)\operatorname{erfc}\left(\frac{\ln\left(\frac{xc}{GMD'}\right)}{\sqrt{2}\,s'}\right)$$

- Uncertainties in denomenator
  - Measurement of penetration (δpen/pen)
    - Pen(x) from AeroCalc
    - δpen/pen from JetsApex2
  - Error associated with the uncertainty in GMD

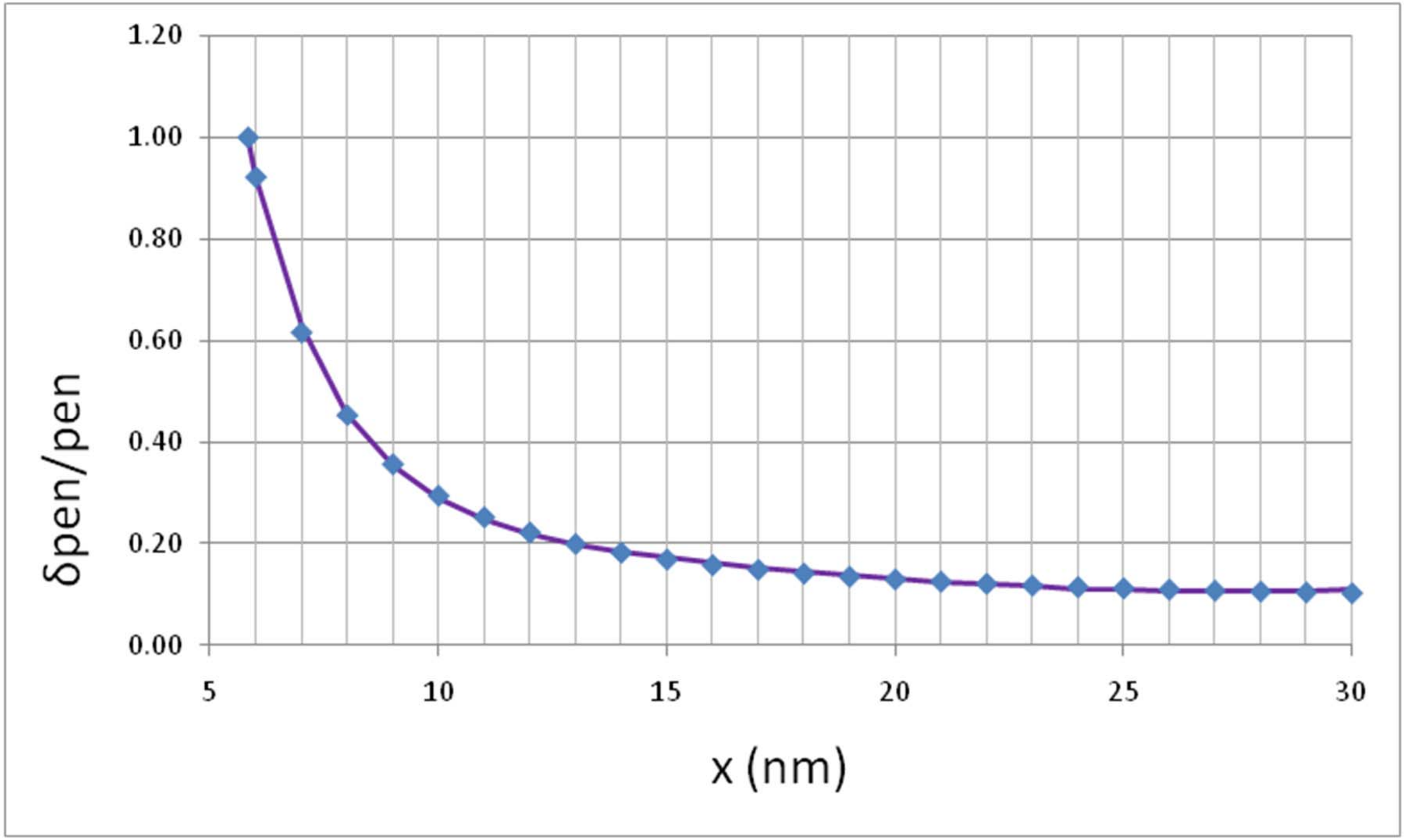
Contributions to δGMD

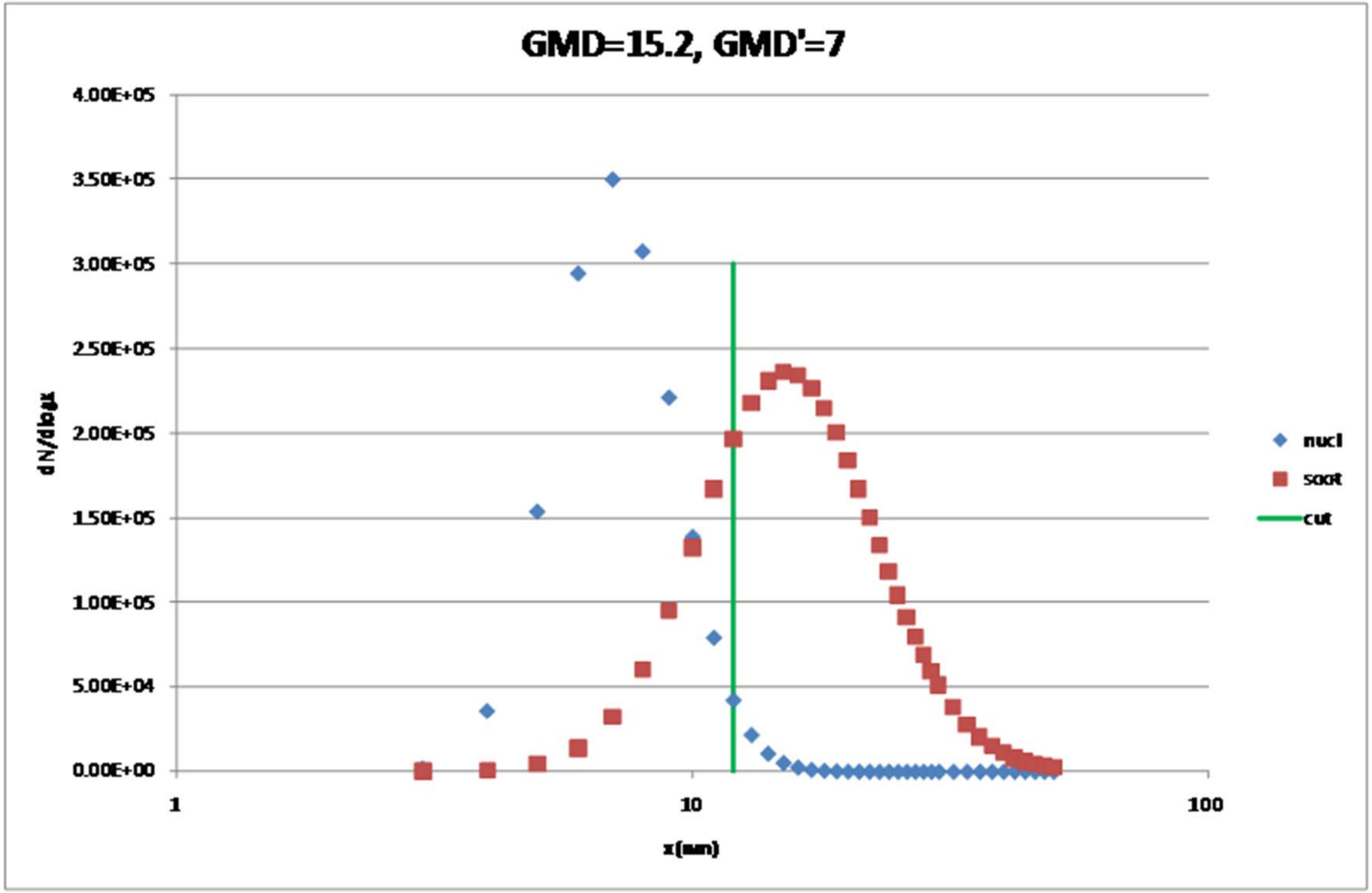
- Error in fitting s=ln(GSD) to GMD
  - $\delta GSD/GSD = 0.042$
  - $s = \ln GSD$; $\delta s = \delta GSD/GSD = 0.042$
  - $(\delta X/X)_{\text{from s-fit}} = (1/X)*(dX/ds)\delta s = (1/X)*(3sX)\delta s = 3s\delta s = 0.126s$
- Normal meas errors in N and M
  - $(\delta N/N)_i = 20\%$
  - $(\delta M/M)_i = 25\%$
- Size cut-off error in N
  - $(\delta N/N)_c = N_{cut}/N$. $\delta X/X = (1/3)*(\delta N/N)_c$
- Combine contributions
  - $\delta X = X*\text{sqrt}\{ (\delta X/X)_{\text{from s-fit}}^2 +(1/9)*[(\delta N/N)_i^2 +(\delta N/N)_c^2 +(\delta M/M)_i^2] \}$

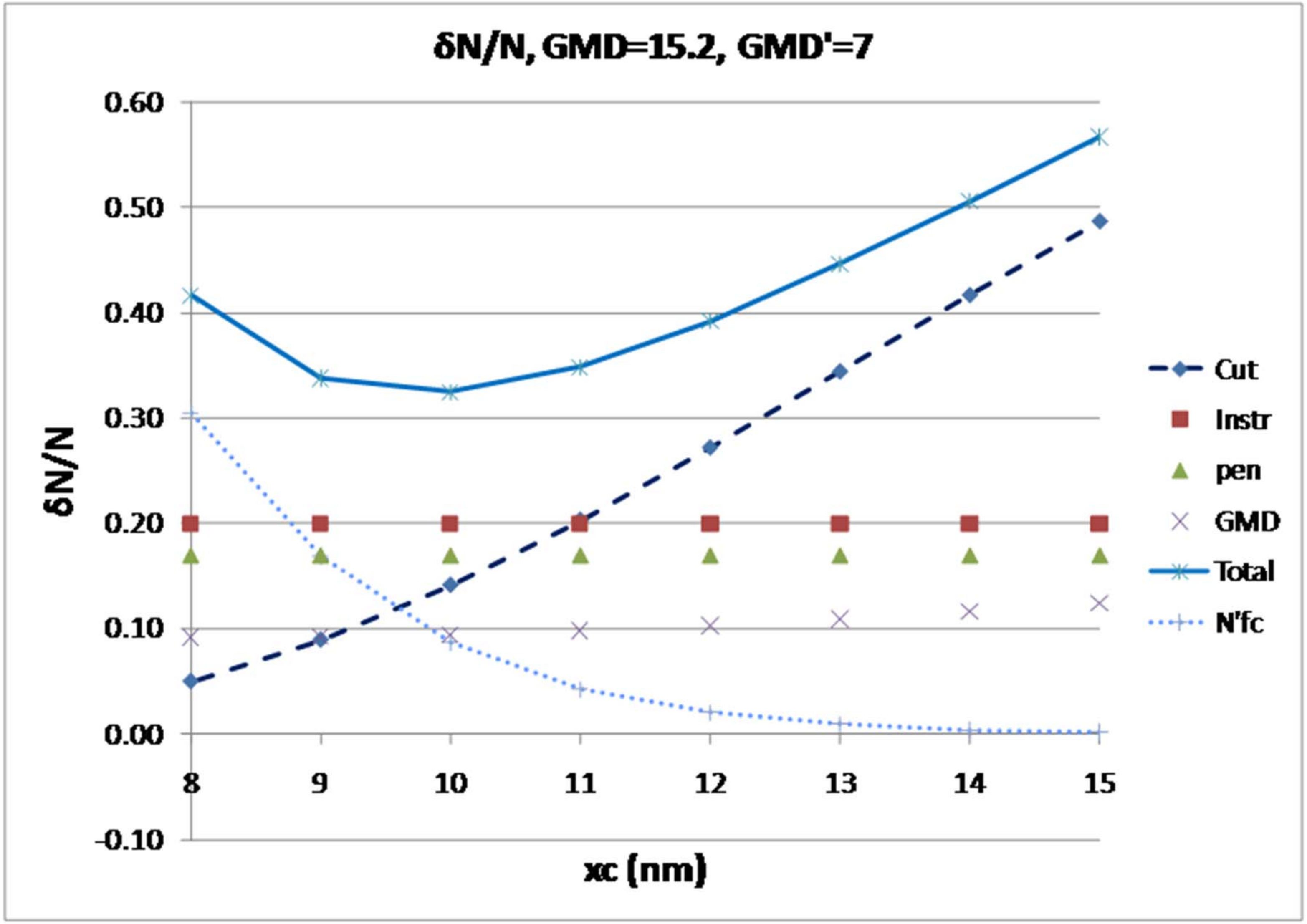

AeroCalc OEM line penetration
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Pen
1
10
100
1000
x (nm)

Uncertainty in line penetration

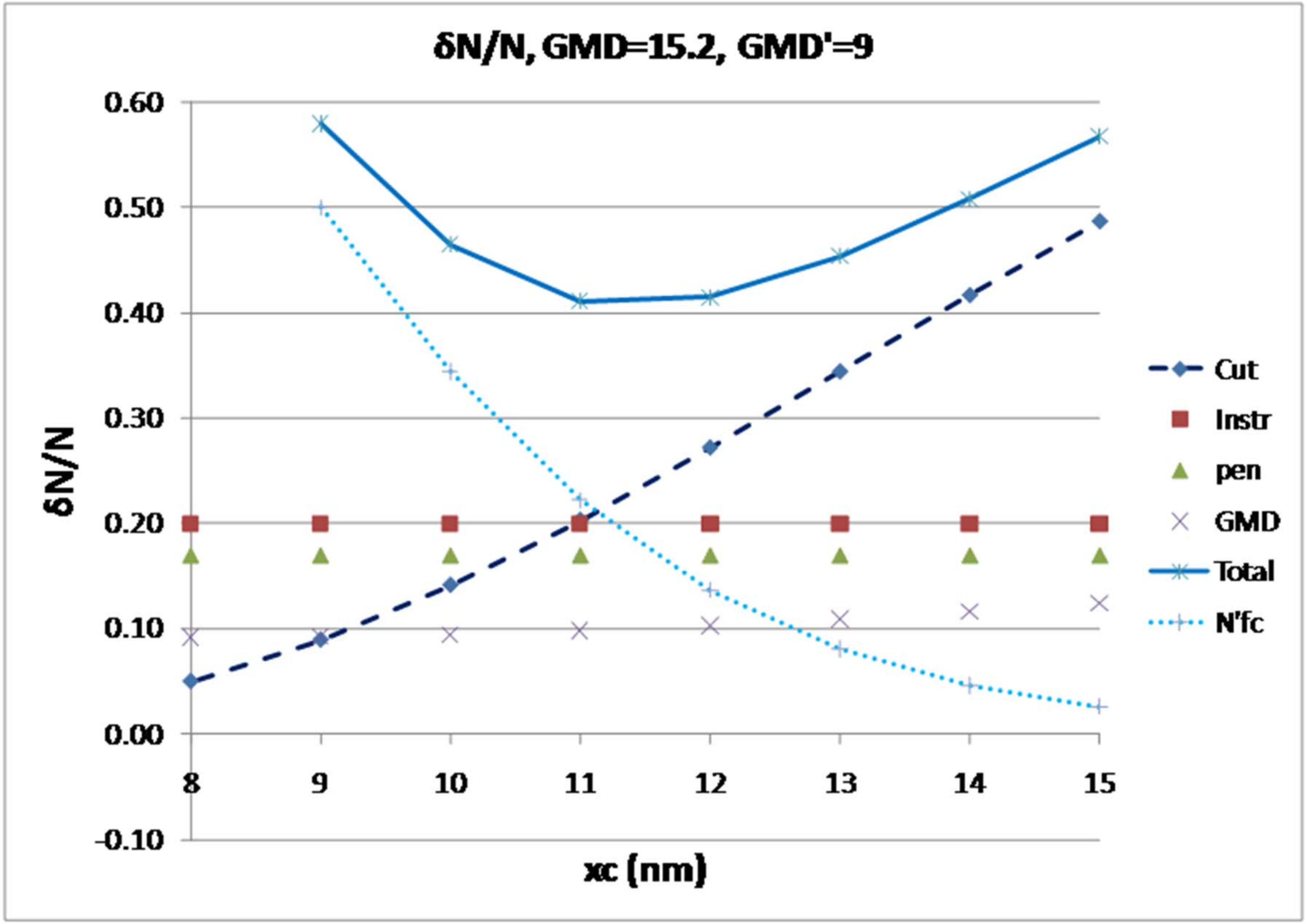
- Taken from Jets Apex2 line loss measurements




GMD=15.2, GMD'=7
4.00E+05
3.50E+05
3.00E+05
2.50E+05
2.00E+05
1.50E+05
1.00E+05
5.00E+04
0.00E+00
dN/dlogx
1
10
100
x(nm)
nucl
soot
cut



δN/N, GMD=15.2, GMD'=7
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
δN/N
8
9
10
11
12
13
14
15
xc (nm)
Cut
Instr
pen
GMD
Total
N'fc


δN/N, GMD=15.2, GMD'=9
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
δN/N
8
9
10
11
12
13
14
15
xc (nm)
Cut
Instr
pen
GMD
Total
N'fc

Conclusions

- For jet engine exhaust sampling a correlation is observed between GSD and GMD.
- The exhaust aerosol's GMD can be estimated from measured number and mass concentrations.
- Uncertainty analysis can be used to estimate the impact of CPC cut-sizes on probe tip number concentration measurement. For soot GMDs near the small end of the range observed in numerous engine test campaigns, the optimum cut size is between 10 and 11 nm.

Acknowledgements

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