Evolution of PM Emissions in the Near Field Plume of a Jet Engine

D.E. Hagen, P. Lobo, and P.D. Whitefield
Center of Excellence for Aerospace Particulate Emissions Reduction Research
Missouri University of Science & Technology
Rolla, MO 65409 USA

The growth of commercial air traffic over the last decade has led to an increased contribution to the local inventory of gaseous and particle emissions from the operations associated with airports and aircraft engines. An accurate assessment requires that the number density and size of the aerosols within engine exhaust and aging plumes be understood and well characterized. The near field jet engine exhaust plume is a dynamic environment, initially at high temperature and rich in small soot particles and relatively high concentrations of water vapor and reactive trace gas species, which then cools by mixing with ambient air promoting gas-to-particle conversion processes leading to dramatic changes in the composition and size distribution of the resulting aerosol. This paper undertakes an experimental investigation of these plume processes, where they occur, how they impact aerosol parameters such as number based geometric mean diameter and emission indices (number or mass of particles generated per kg of fuel burned), and how they are impacted by engine operating conditions.

This paper focuses on two engines that are well represented in the current US commercial airline fleet: JT8D and CFM56. The JT8D is a low by-pass engine manufactured by Pratt & Whitney, was first introduced in 1964, has a thrust range from 62-77 kN, and is used on 727, 737-200, DC-9, and MD-80 aircraft. It represents about 1/3 of current commercial engines. The CFM56 is a high by-pass engine manufactured by CFM International (GE and SNECMA), was first introduced in 1974, has a thrust range from 82-151 kN, and is used on E3, E6, KC/RC135, DC8, 737, A318-21, and A340 aircraft. It is reported to be the best selling engine in commercial aviation history. Emissions data for these engines was collected in four measurement campaigns: APEX1 conducted in April 2004 at NASA Dryden, Delta-Atlanta Hartsfield Study conducted in September 2004 at Hartsfield Jackson Atlanta airport, JETS-APEX2 conducted in August 2005 at Oakland airport, and APEX3 conducted in November 2005 at Cleveland Hopkins airport. During engine test facets of the campaigns, engine emissions were extracted from the plumes using sampling probes at 1m and 50m from the engine exit plane, and transported through a sample train to instruments located in nearby mobile laboratories. These samples were taken from specific on-wing engines of different aircraft whose engines were cycled through a matrix of reproducible engine operating conditions. During advected plume experiments, engine emissions were sampled with probes located about 150m downwind from active runways during normal airport operations. These measurements were performed on a non-interference basis, so that normal airport operations could continue without being affected by the measurement teams' activities.

Two observations influenced the way data processing was handled. APEX1 employed probes at 1m, 10m, and 30m from the engine exit plane. The 10m probe exhibited emissions data that was close to that found from the 1m probe, indicating that aerosol parameters were not changing significantly during the first 10m of the plume.

The advected plume data taken during the Delta Atlanta-Hartsfield Study showed little variation between samples of the same engine type for fixed atmospheric conditions. Since the plume distance varied from sample to sample due to variations in wind direction and speed, the aerosol parameters were relatively stable at 150m. The function (cubic polynomial) used to fit aerosol data as a function of plume distance was therefore constrained to have zero slope at distances zero and 150m.

An uncertainty weighted constrained linear least squares fit was performed for selected aerosol parameters (number (Dgn) and mass (Dgm) based geometric mean diameters, geometric standard deviation, and number (EIn) and mass (EIm) based emission indices) as a function of plume distance. The uncertainties in the measurements reflected both variations in repeated measurements on the same engine along with observed differences between different samples from the same engine type. Using the functional fit with its associated uncertainties, a plume distance was found at which the change in aerosol parameter from its exit plane value became statistically meaningful, i.e. the error bars didn't overlap. Table 1 exhibits these distances for the various aerosol parameters and engine operating conditions. In some cases no statistically meaningful change was reached, and the table entry is left blank.

Table 1. Distance downstream from engine for significant plume effects

CFM56 Model	Operating Condition	Dist(m) Dgn	Dist(m) Sigma	Dist(m) Dgm	Dist(m) EIn	Dist(m) EIm
3B/C,7B	Idle	-	-	-	64	31
3B/C	TO	37	-	-	26	-
7B	TO	53	22	12	15	64

Another measure of plume processing is the ratio of advected plume to its engine exit plane values for the aerosol parameters. These have been calculated using the functional fits and are exhibited in Table 2.

Table 2. Ratio (Adv plume / EEP)

Parameter	Idle 3B/C,7B	TO - 3B	TO - 7B	JT8D
Dgn	-	0.19	0.41	0.23
EIn	20	134	134	8.7
EIm	33	1.4	4.4	1.9

In conclusion, plume processing is observed for the JT8D and CFM56 engines. Major changes are observed in Dgn and EIn. Dgn decreased by factors ranging from 0.2 to 0.4, and EIn increased by factors ranging from 9 to 130. Plume processing becomes significant at distances from 12 to 64m downstream of the engine exit plane. The plume is observed to be stable at 150m; its standard deviation is observed to be 3.8% for the CFM56 and 1.1% for the JT8D.

Center of Excellence for Aerospace Particulate Emissions Reduction Research

Evolution of PM Emissions in the Near Field Plume of a Jet Engine

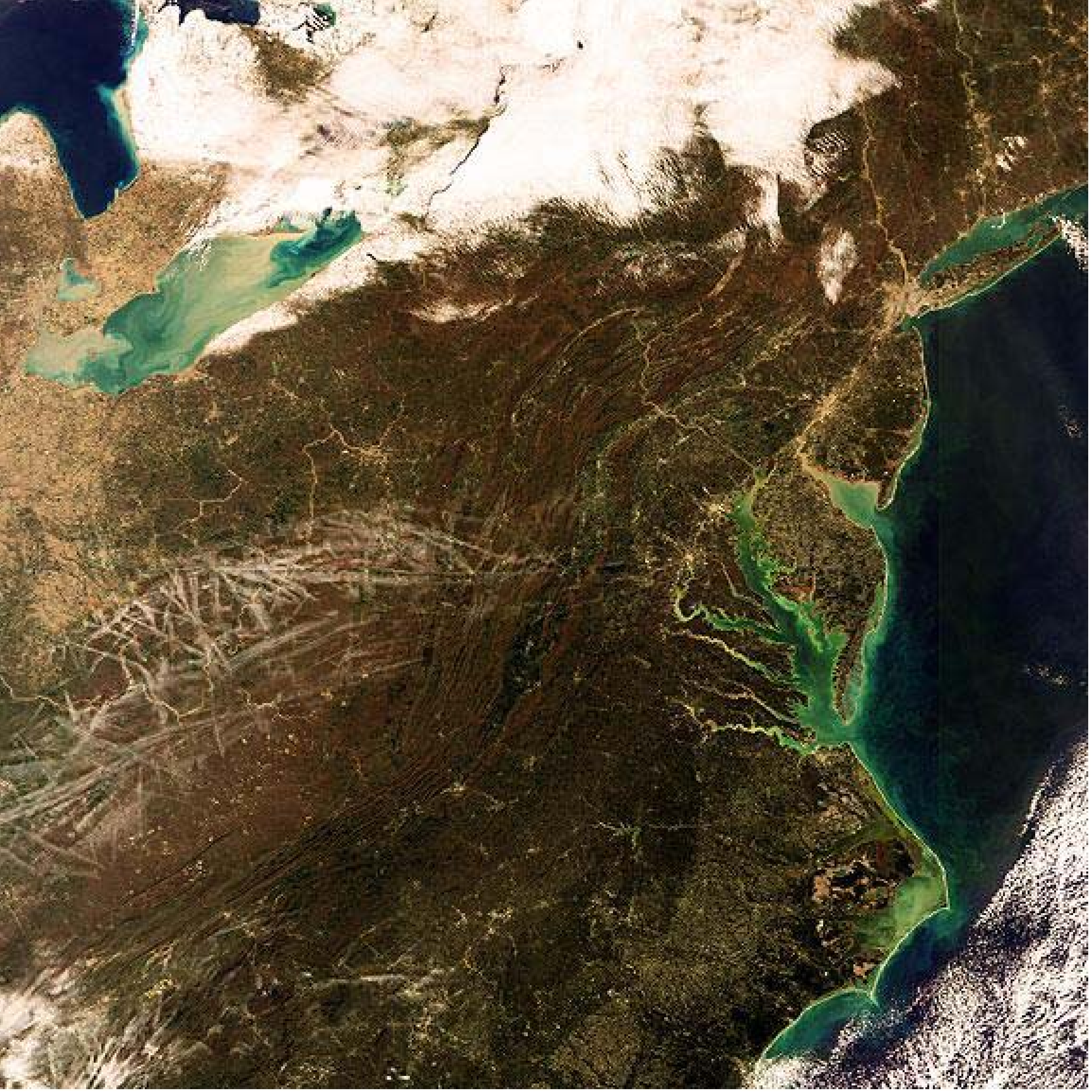
Donald Hagen, Prem Lobo and Philip Whitefield

12th ETH-Conference on Combustion Generated Nanoparticles
Zurich, Switzerland
June 23-25, 2008

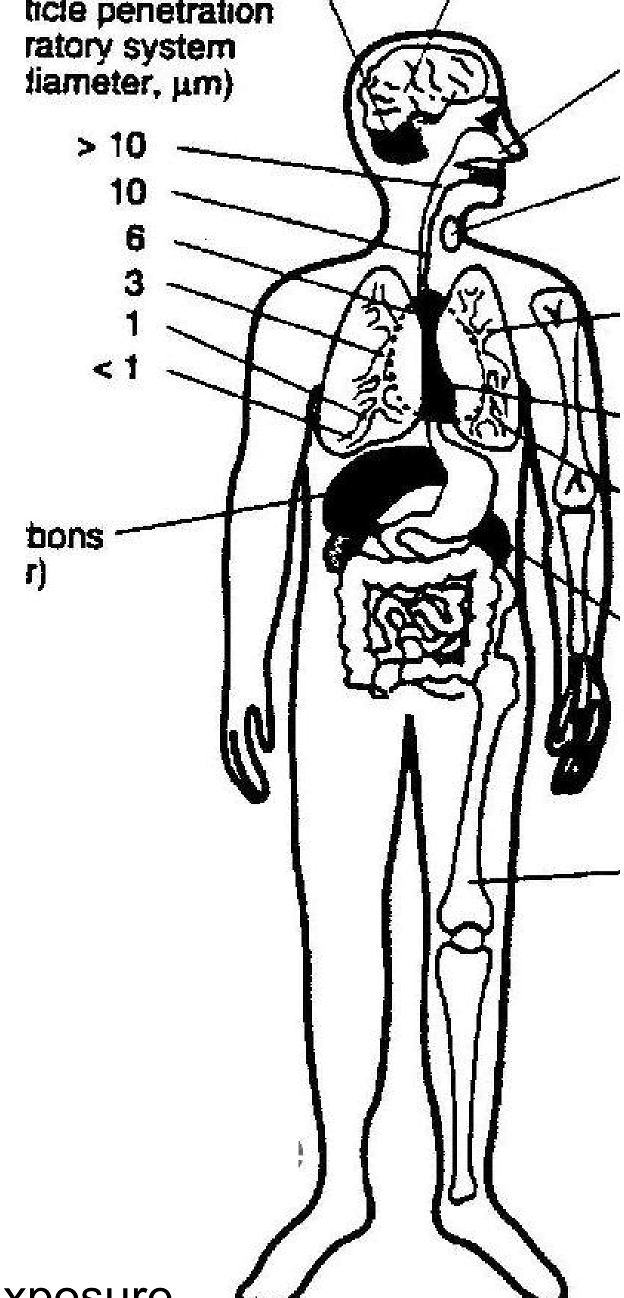
This work was funded by

- FAA under FAA Grant No: 03-C-NE-UMR, Amendment Nos. 001,002, 003, 004, 005, and 007
- NASA under Contract No: NCC3-1084
- California Air Resources Board under ARB contract number 04-344

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the FAA, NASA, or California Air Resources Board .



Climate Change



R. Turco
Effects of Exposure
To Pollution

Health Effects

Focus on Two Engine Types

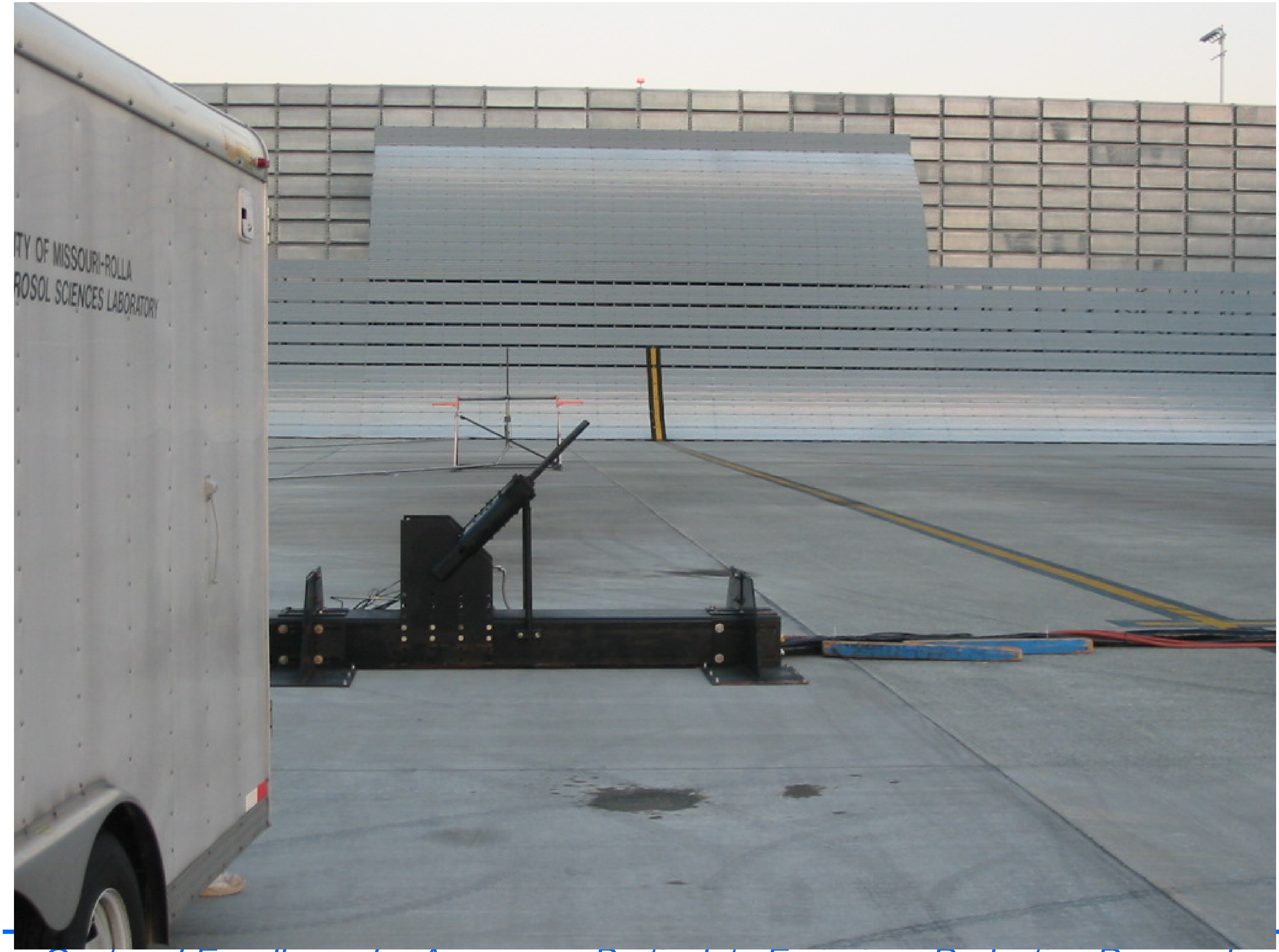
- **JT8D**
- Pratt & Whitney
- Vintage 1964
- Thrust 62-77 kN
- Low by-pass
- ~1/3 of fleet
- 727, 737-200, DC-9, MD-80

- **CFM56**
- CFM (GE & Snecma)
- 1974 (7B – 1996)
- Thrust 82-151 kN
- High by-pass
- Best selling engine in aviation history
- E3, E6, KC/RC135, DC8, 737, A318-21, A340

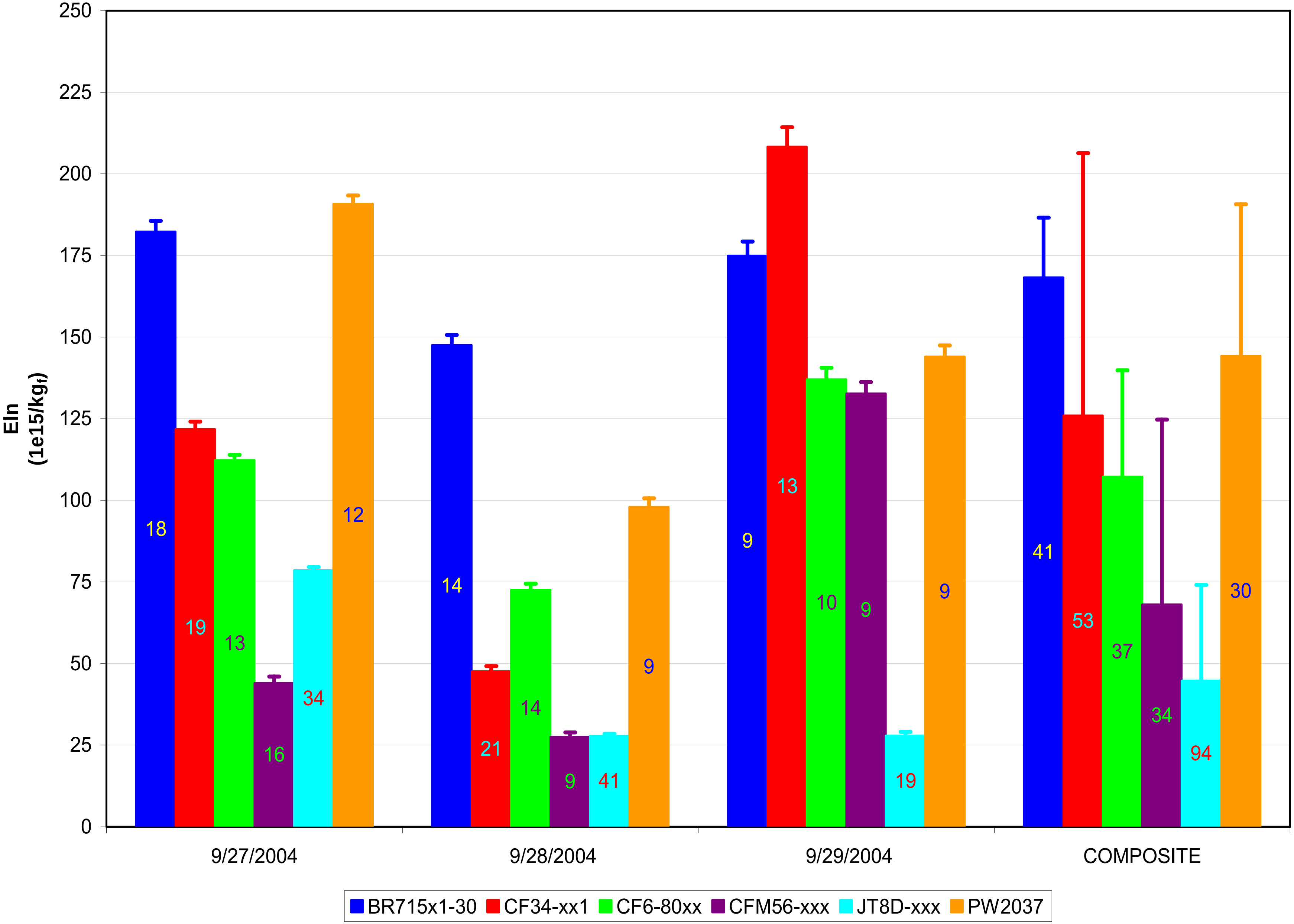
Campaigns

- APEX: Apr 2004, NASA Dryden, CA
- Delta – Atlanta Hartsfield: Sep 2004
- JETS-APEX2: Aug 2005, Oakland
- APEX3: Nov 2005, Cleveland


SOUTHWEST


TY OF MISSOURI-ROLLA
ROSOL SCIENCES LABORATORY


Street Map
Aerial Image
Show labels
College Park
Airport Blvd
Perry J Hudson Pkwy
N Central Ave
Virginia Ave
Main St
Lee St
Fulton
Clayton
Hartsfield-Jackson
Atlanta Int'l
Loop Rd S
I-75 Hov Ln
Riverdale Rd
85
75
285
239
237A
238A
58
59
70
72
400 m
1200 ft
MAPQUEST
© 2007 MapQuest Inc. © 2007 i-cubed © 2007 NAVTEQ


EIn
(1e15/kg$_f$)
250
225
200
175
150
125
100
75
50
25
0
18
19
13
16
34
12
14
21
14
9
41
9
9
13
10
9
19
9
41
53
37
34
94
30
9/27/2004
9/28/2004
9/29/2004
COMPOSITE
BR715x1-30
CF34-xx1
CF6-80xx
CFM56-xxx
JT8D-xxx
PW2037

Aerosol parameter (plume dist.)

- Fit with a cubic polynomial.
- Used linear coef. to force slope to zero at EEP (APEX result)
- Used cubic coef. to force slope to zero at 150m (ATL result)

Measurements $\{x_i, y_i, \sigma_i\}$

$y = a_1 + a_0 x + a_2 x^2 + a_3 x^3$

$dy/dx = 0$ at $x = 0$,

$x^* = 150\text{m}$

x = Plume dist

y = Dgn, Dgm, EIn,...

σ = Uncertainty

$y_i = \Sigma_m C_{im} a_m \quad m=1,2$

$C_{i1} = 1$

$C_{i2} = x_i^2 - 2x_i^3/3x^*$

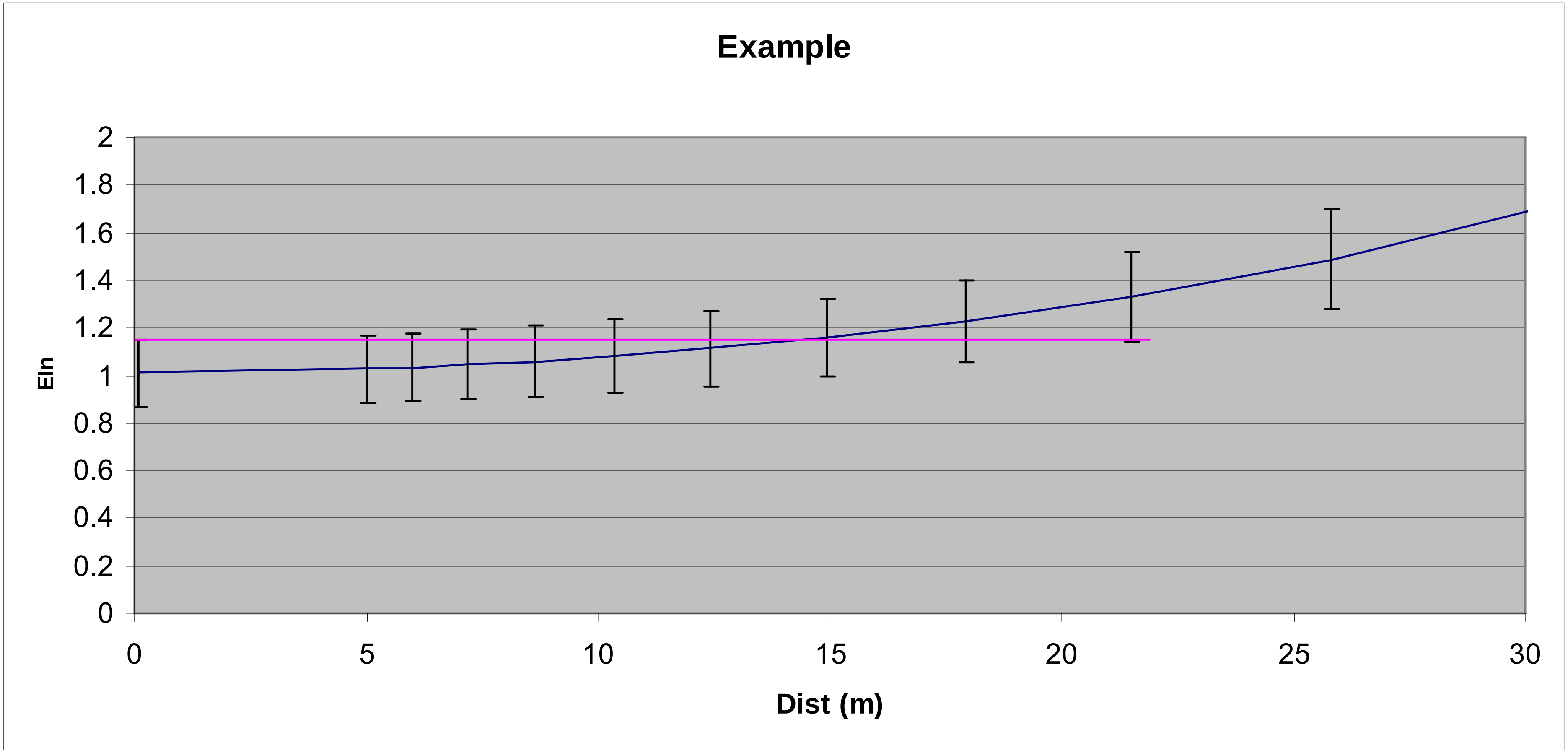
$Y_m = \Sigma_i (C_{im} y_i)/\sigma_i^2$

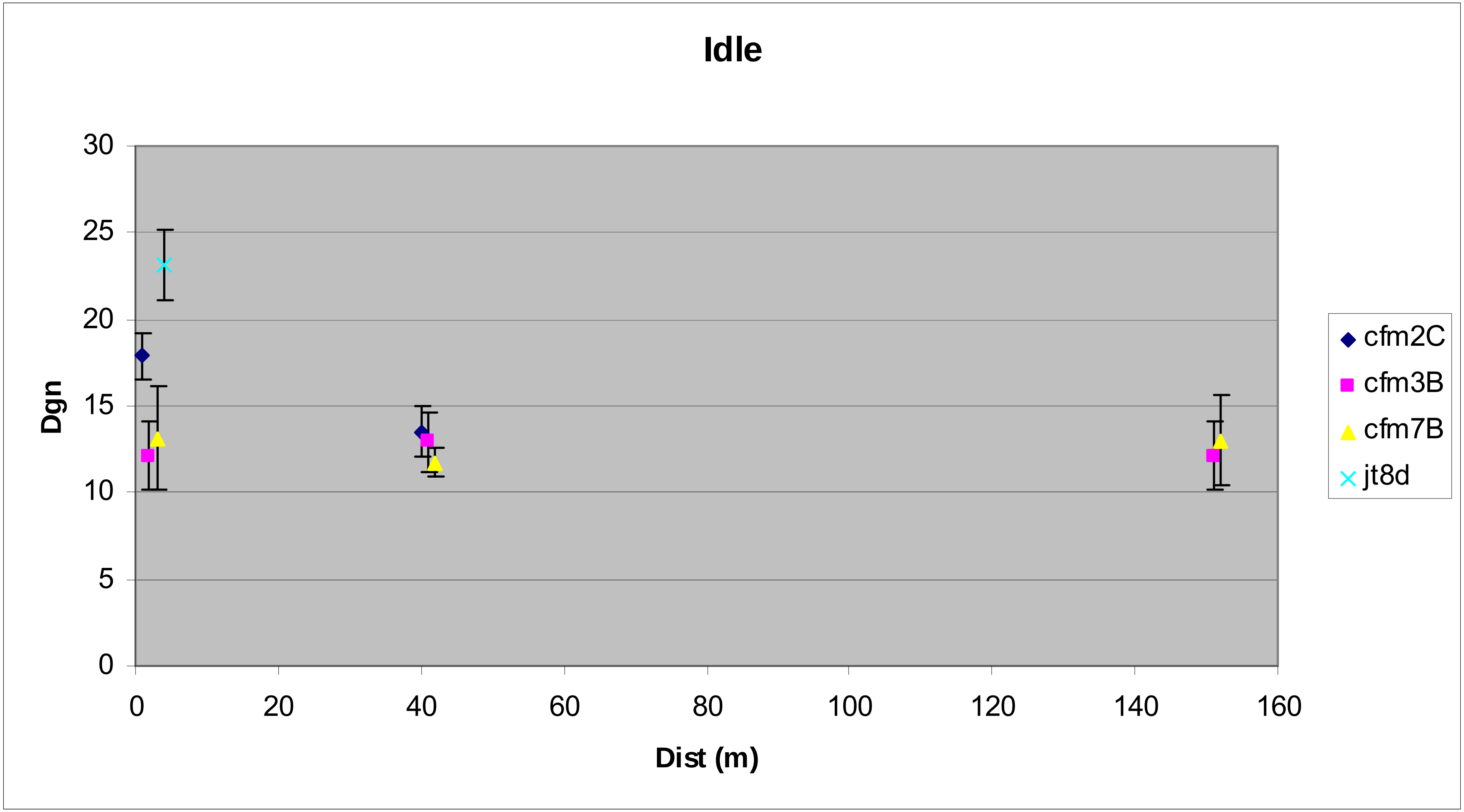
$M_{mn} = \Sigma_i (C_{im} C_{in})/\sigma_i^2$

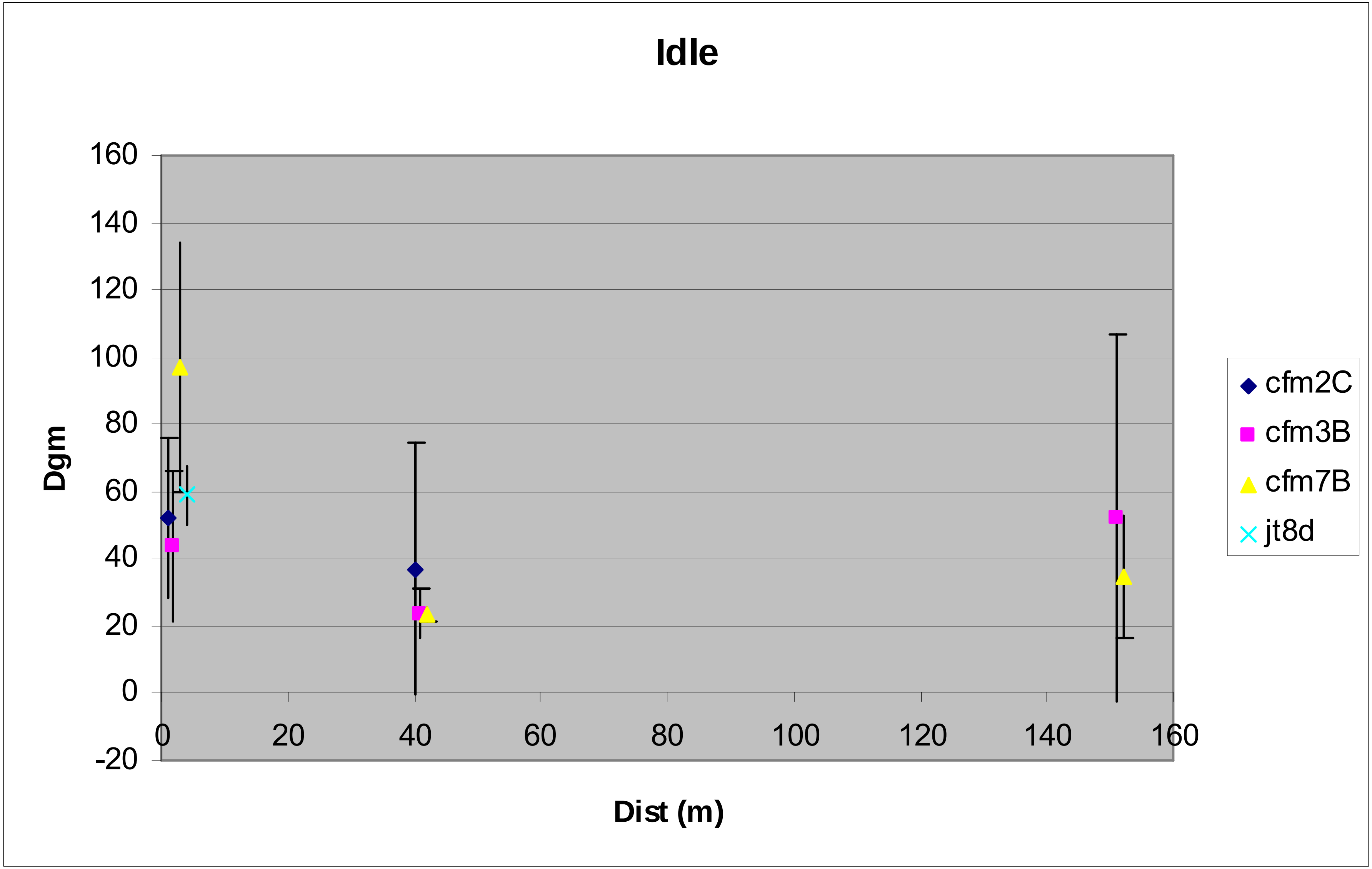
$Y = Ma$

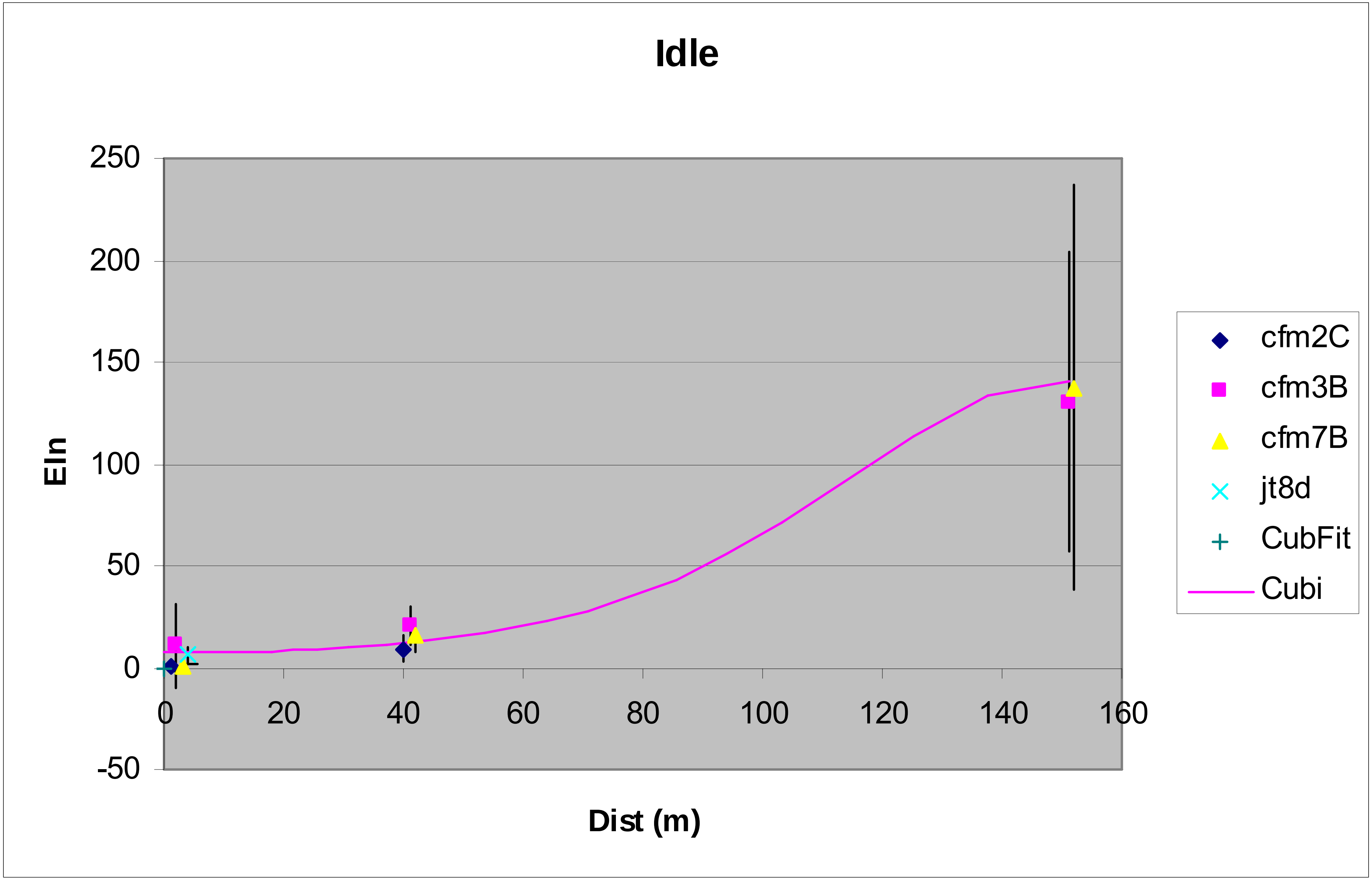
$a = M^{-1} Y$

$\Delta a_m = [(M^{-1})_{mm}]^{1/2}$

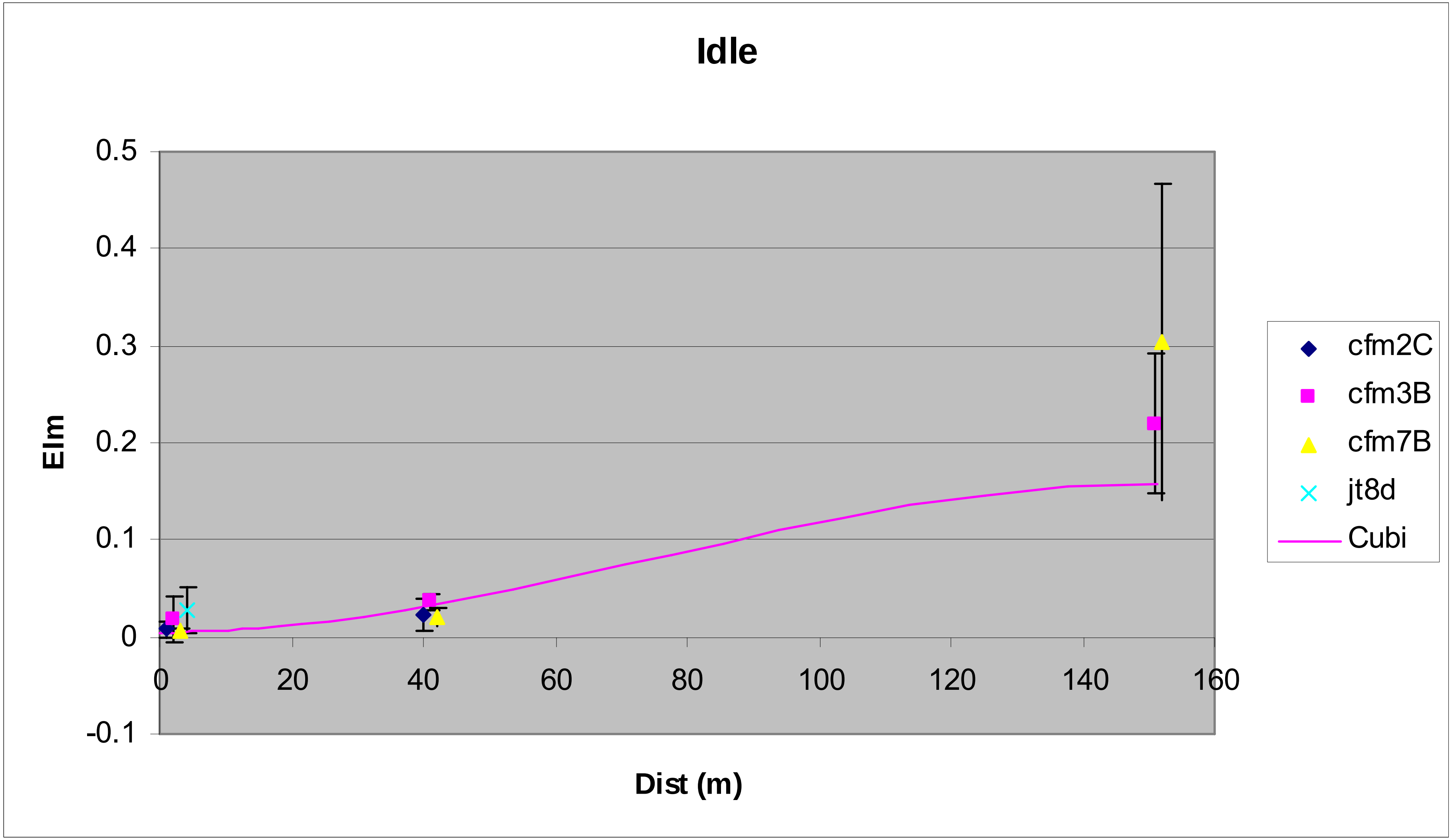

Example
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Eln
0
5
10
15
20
25
30
Dist (m)


Idle
30
25
20
15
10
5
0
Dgn
0
20
40
60
80
100
120
140
160
Dist (m)
cfm2C
cfm3B
cfm7B
jt8d

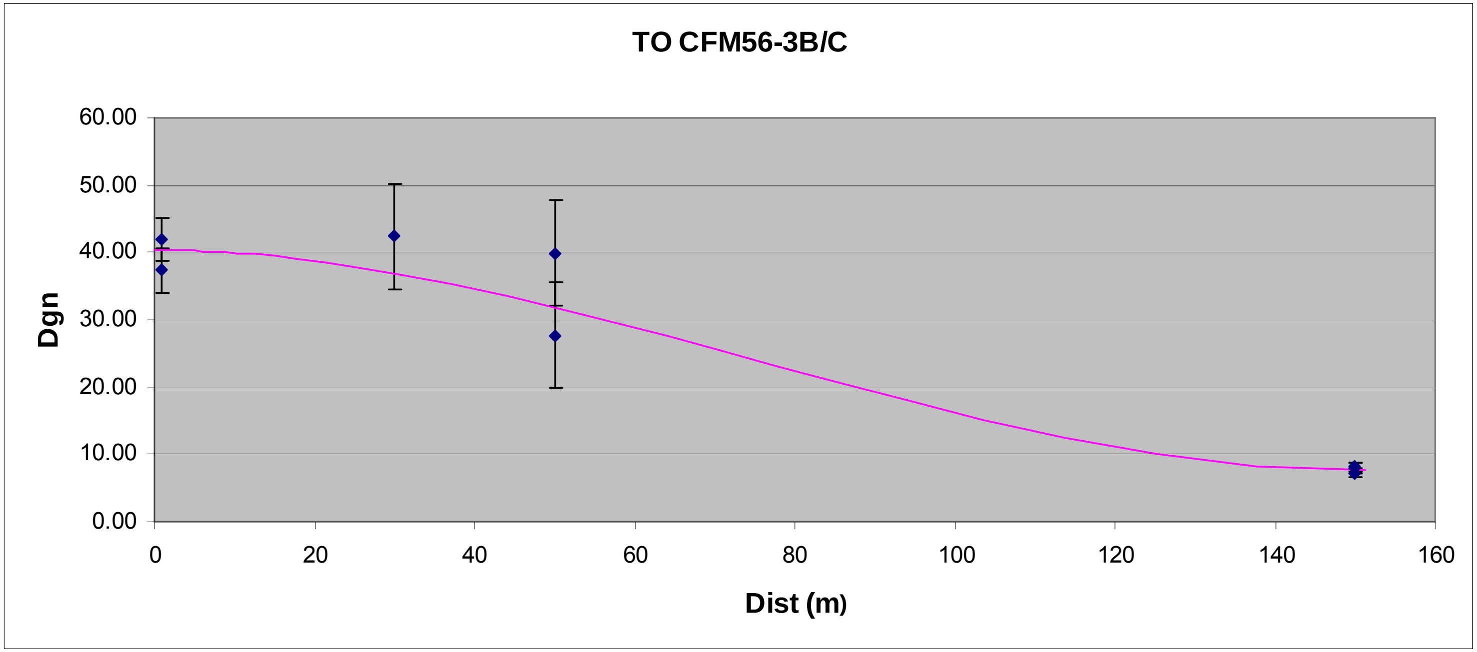

Idle
160
140
120
100
80
60
40
20
0
-20
Dgm
0
20
40
60
80
100
120
140
160
Dist (m)
cfm2C
cfm3B
cfm7B
jt8d

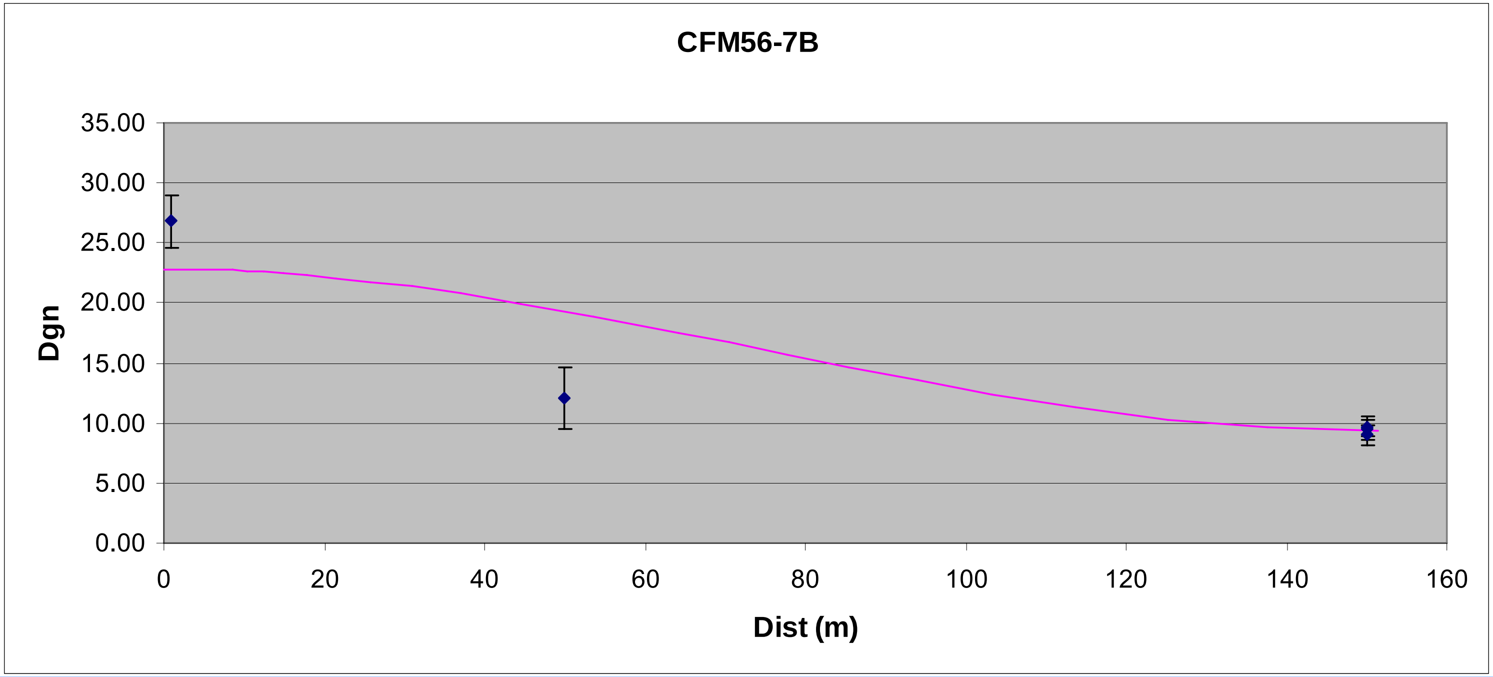


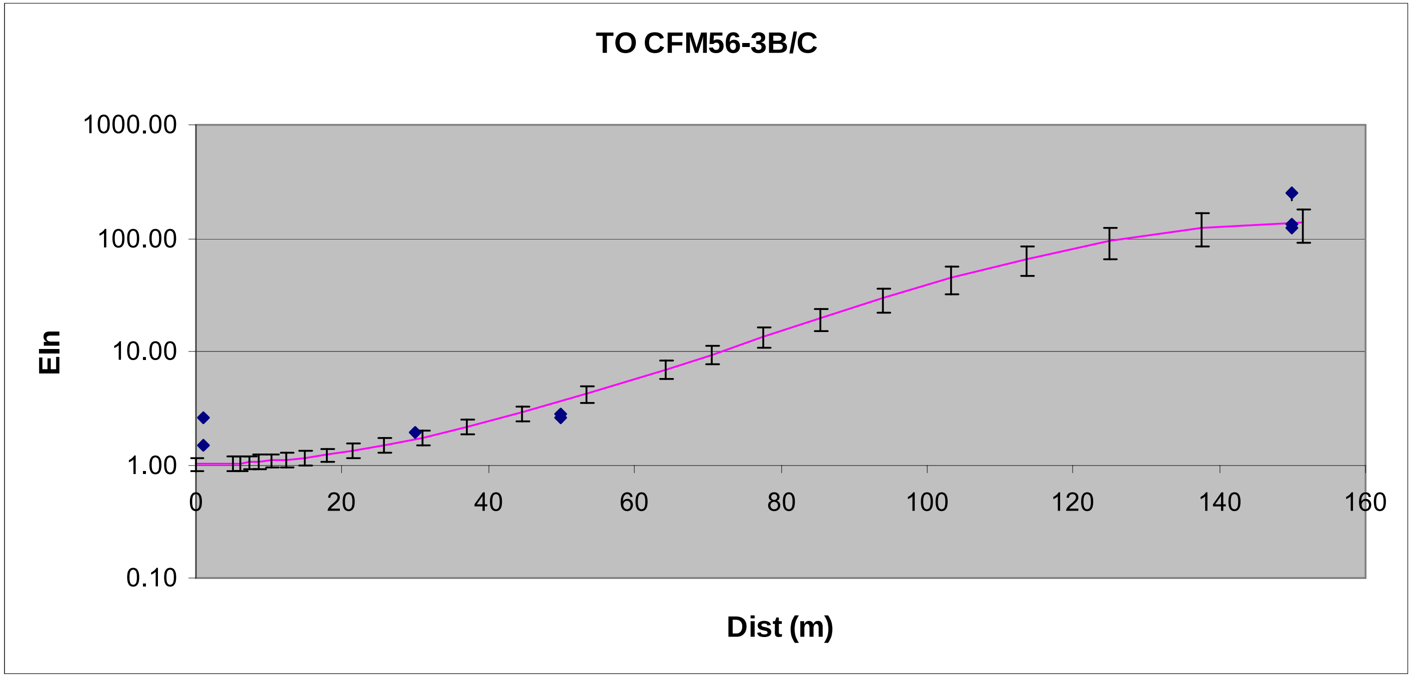
Idle
250
200
150
100
50
0
-50
Eln
0
20
40
60
80
100
120
140
160
Dist (m)
cfm2C
cfm3B
cfm7B
jt8d
CubFit
Cubi

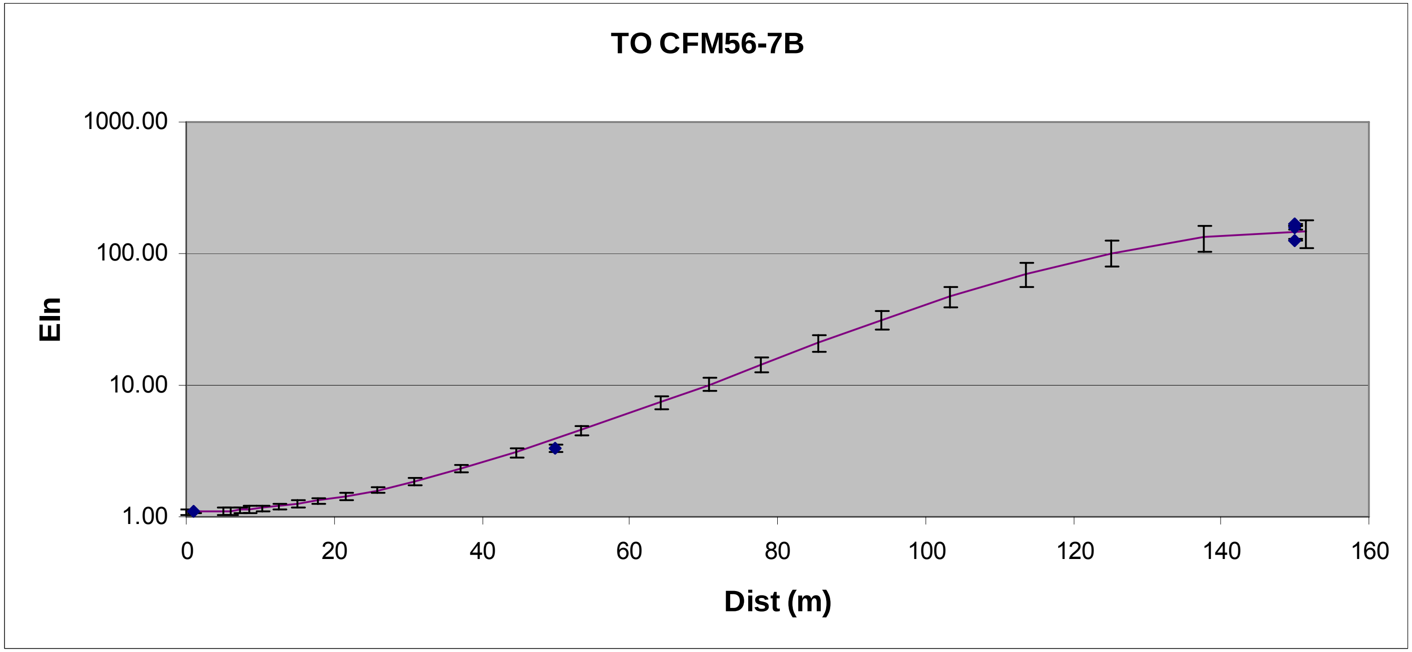


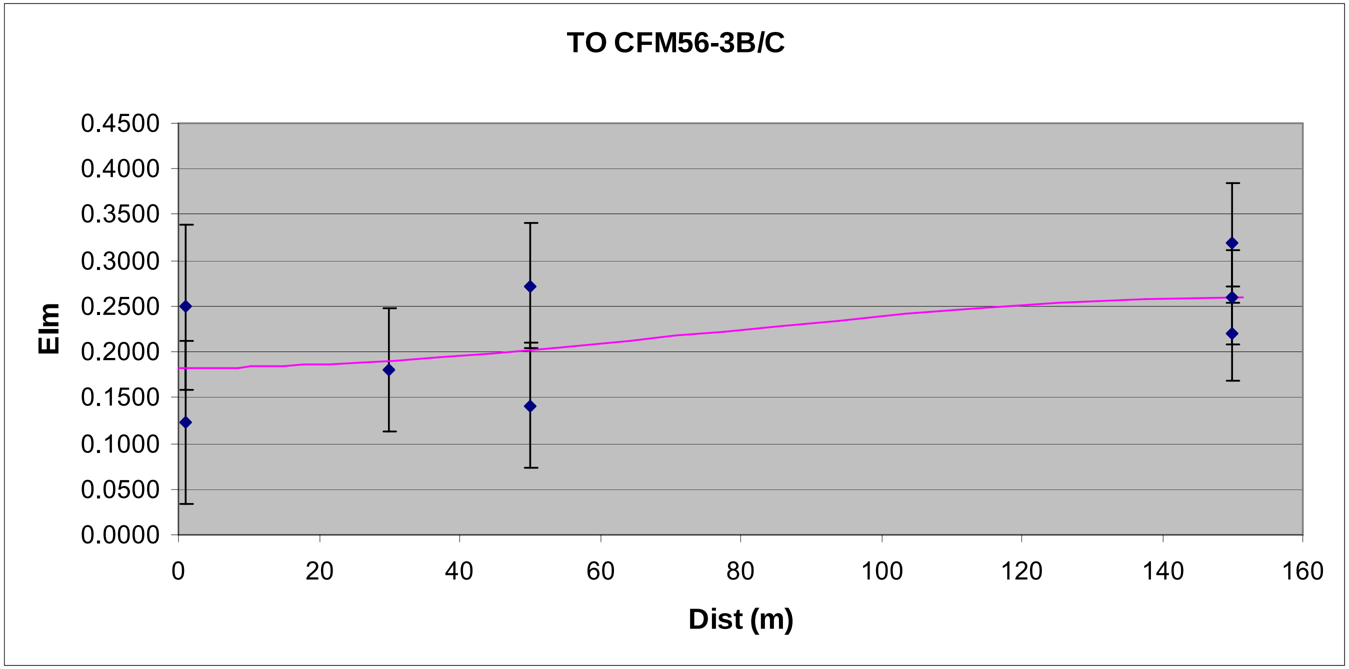
Idle
0.5
0.4
0.3
0.2
0.1
0
-0.1
Elm
0
20
40
60
80
100
120
140
160
Dist (m)
cfm2C
cfm3B
cfm7B
jt8d
Cubi

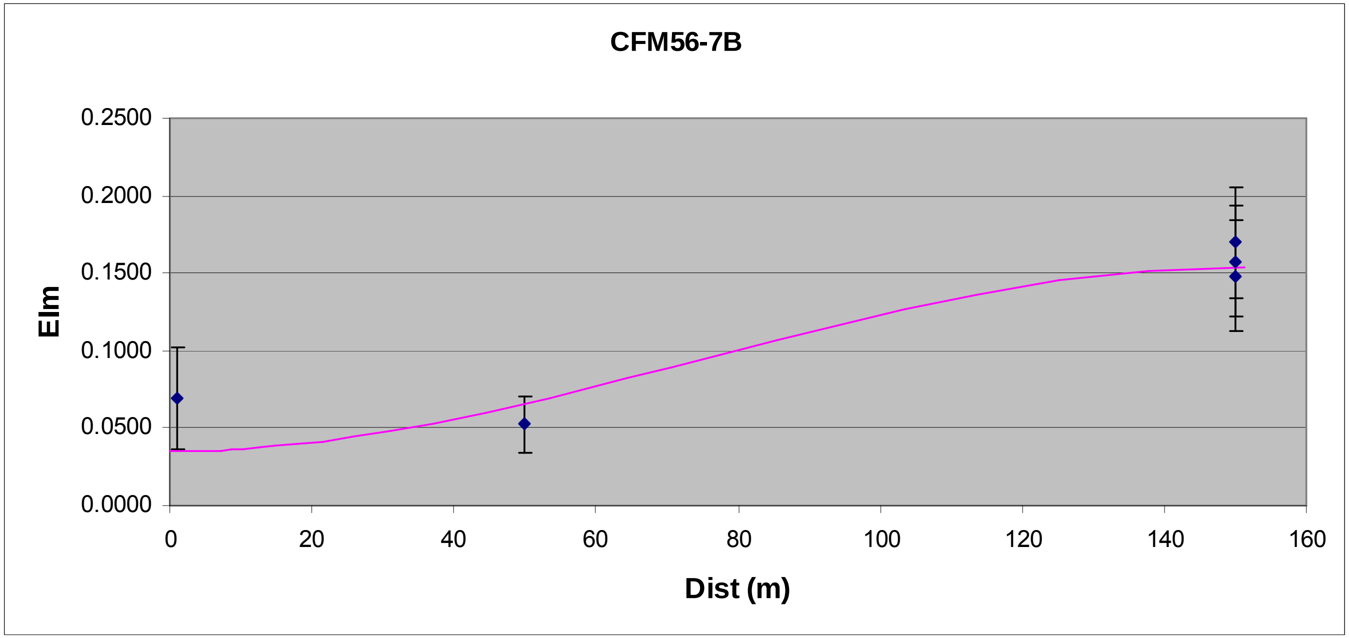

TO CFM56-3B/C
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Dgn
0
20
40
60
80
100
120
140
160
Dist (m)


CFM56-7B
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Dgn
0
20
40
60
80
100
120
140
160
Dist (m)


TO CFM56-3B/C
1000.00
100.00
10.00
1.00
0.10
EIn
0
20
40
60
80
100
120
140
160
Dist (m)

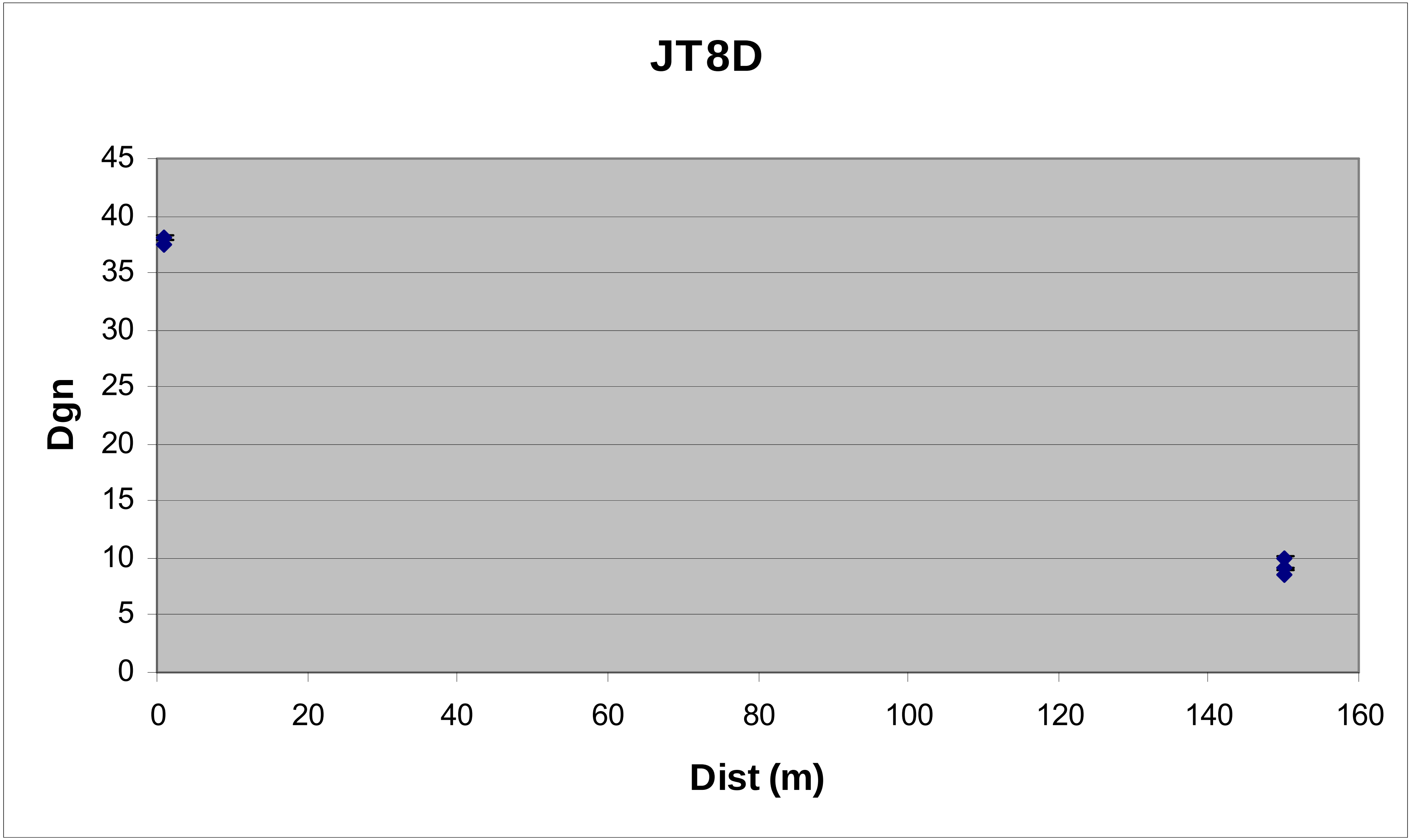

TO CFM56-7B
1000.00
100.00
10.00
1.00
EIn
0
20
40
60
80
100
120
140
160
Dist (m)


TO CFM56-3B/C
0.4500
0.4000
0.3500
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
Elm
0
20
40
60
80
100
120
140
160
Dist (m)

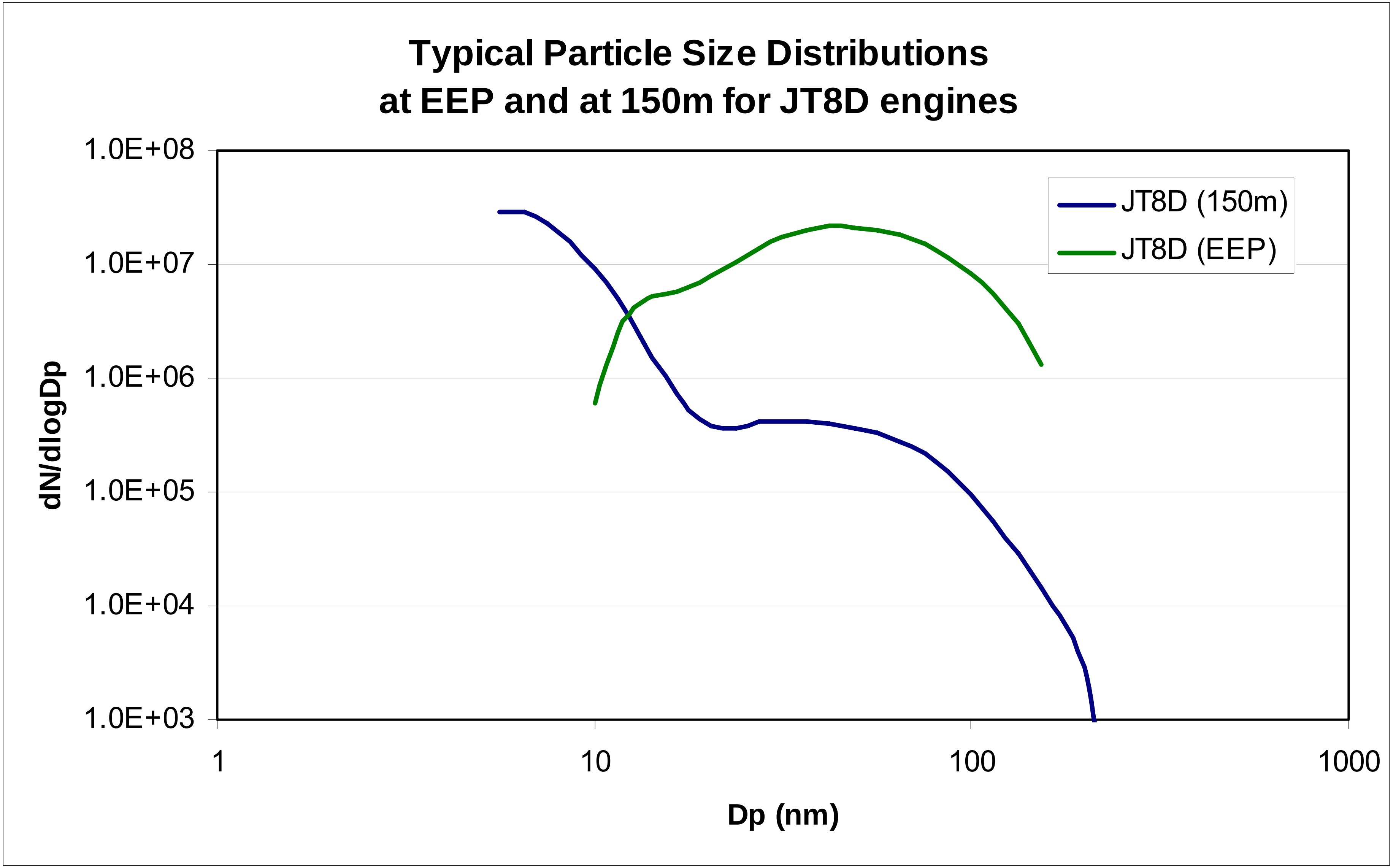

CFM56-7B
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
Elm
0
20
40
60
80
100
120
140
160
Dist (m)

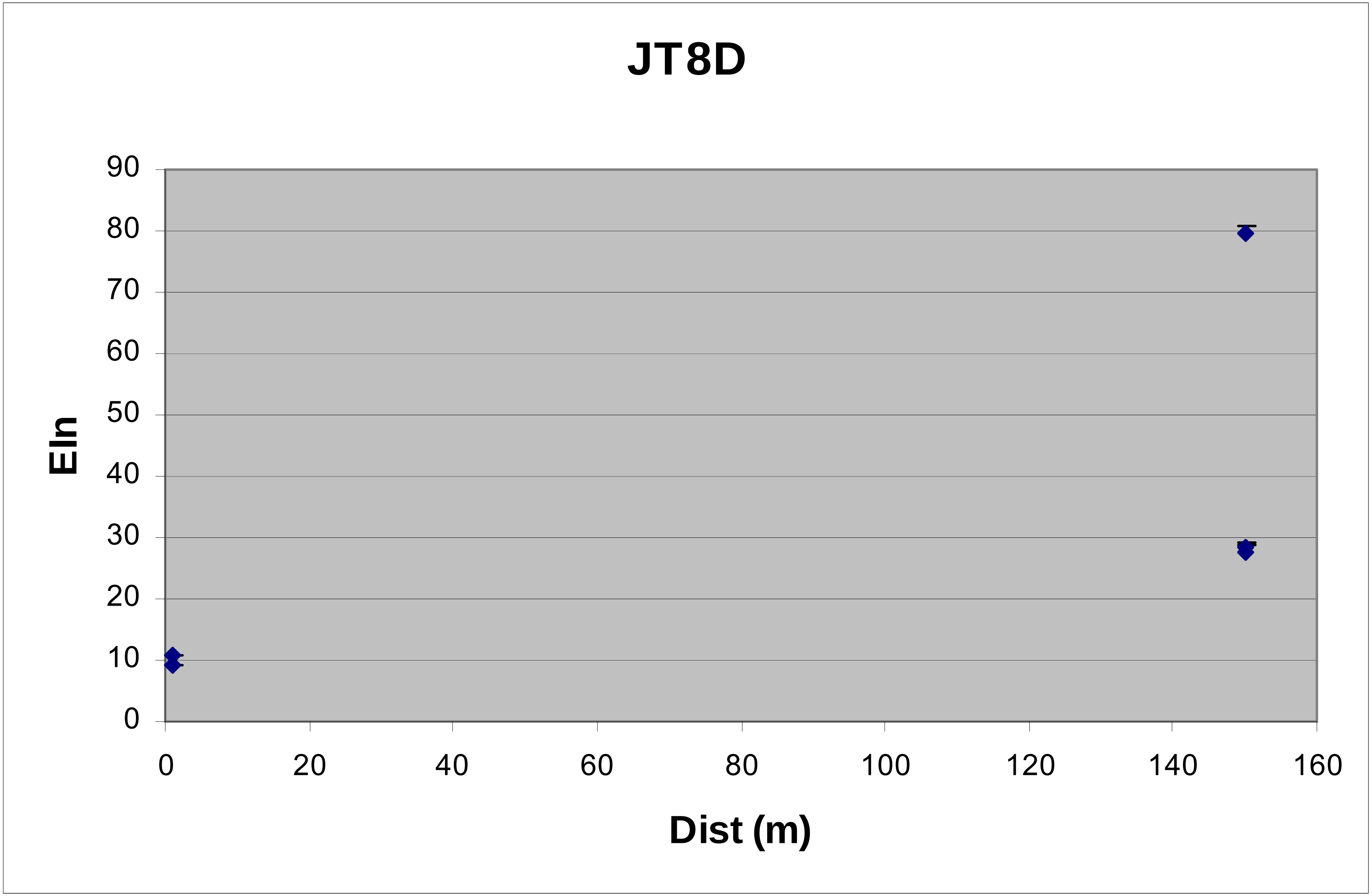
Distance downstream from engine for significant plume effects

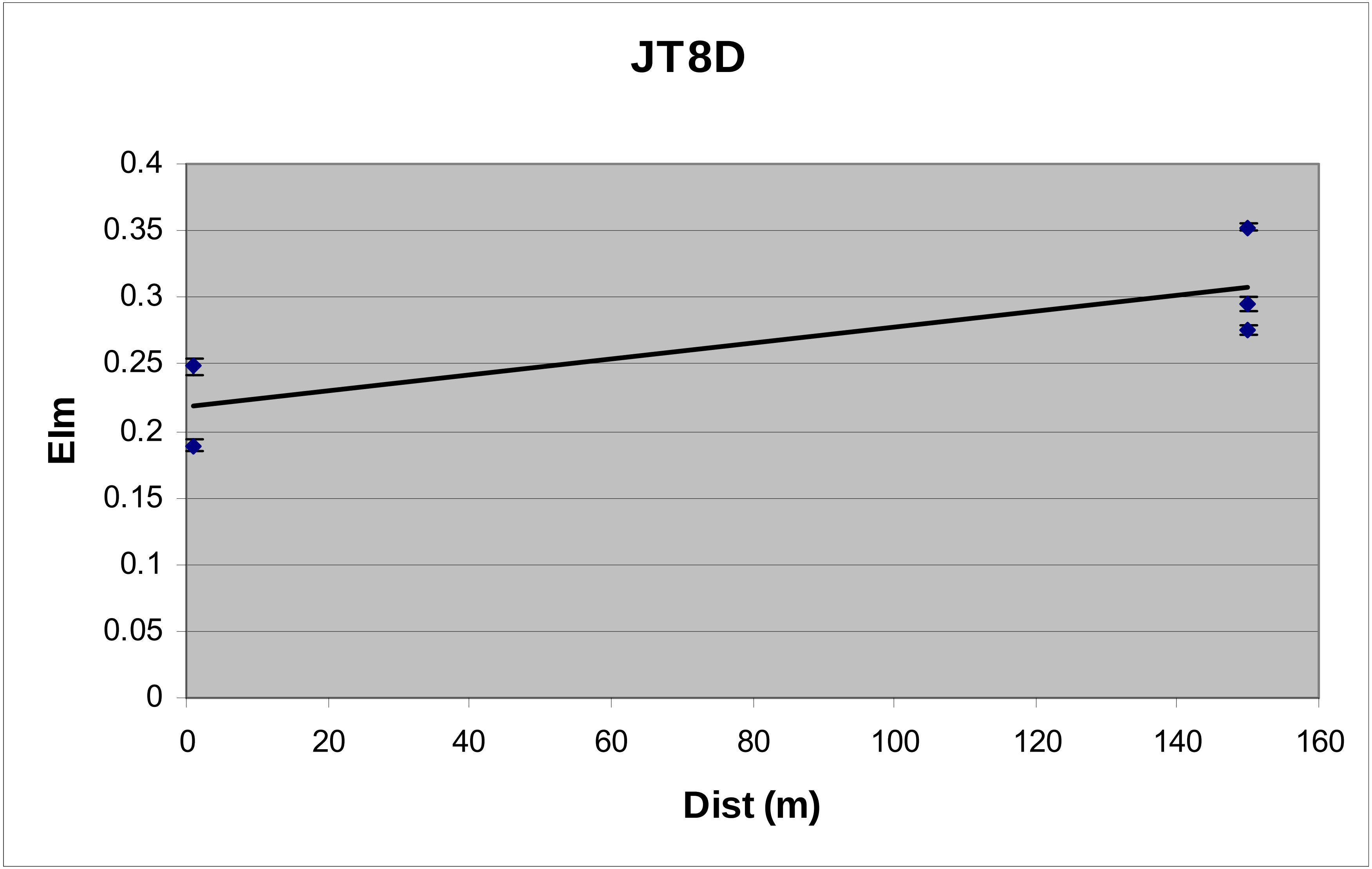
CFM56 Model	Operating Condition	Dist(m) Dgn	Dist(m) Sigma	Dist(m) Dgm	Dist(m) EIn	Dist(m) EIm
3B/C,7B	Idle	-	-	-	64	31
3B/C	TO	37	-	-	26	-
7B	TO	53	22	12	15	64



JT8D
Dgn
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
Dist (m)


Typical Particle Size Distributions
at EEP and at 150m for JT8D engines
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
dN/dlogDp
1
10
100
1000
Dp (nm)
JT8D (150m)
JT8D (EEP)


JT8D
Eln
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
Dist (m)



JT8D
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Elm
0
20
40
60
80
100
120
140
160
Dist (m)

Ratio (Adv plume / EEP)

Parameter	Idle 3B/C,7B	TO - 3B	TO - 7B	JT8D
Dgn	-	0.19	0.41	0.23
EIn	20	134	134	8.7
EIm	33	1.4	4.4	1.9

Conclusions

- Plume processing is observed for JT8D and CFM56 engines.
- Major changes reflected in Dgn and EIn
  - Dgn decreases by factors 0.2 to 0.4.
  - EIn increases by factors 9 to 130.
- Plume processing becomes active at distances of 12 to 64m downstream of EEP
- Plume stable at 150m:
  - 3.8% for CFM56
  - 1.1% for JT8D

Acknowledgements

- The APEX Studies research teams
- FAA, NASA, EPA, DOD, CARB
- Delta, Southwest, Continental, and Continental Express airlines
- Hartsfield-Jackson Atlanta International, Oakland International and Cleveland Hopkins International Airports
- FedEx, GEAE, P&W, RR and Boeing