Comprehensive Characterization of Particulate Emissions from Advanced Diesel Combustion

Prof. David E. Foster

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Acknowledgement

- Horiba
- Cummins Filtration
- BP-Amoco
- ORNL
- Dr. Terunao Kawai
- Prof. Takeyuki Kamimoto

Goal of Research

Particulate Instruments

- AVL Smoke Meter 415S (mass conc.)
- TSI SMPS (particle size distribution)
- R&P TEOM (mass conc.)
- Horiba MEXA 1370PM (chemical speciation)
- Teflon Gravimetric (mass conc.)
- NIOSH EC/OC (chemical speciation)
- Microwave Extraction Soot/SOF (chemical speciation)

LTC vs. Conventional Diesel PM

- High Load Conventional
- Medium Load Conventional
- Medium Load LTC, High Injection Pressure
- Medium Load LTC, Low Injection Pressure

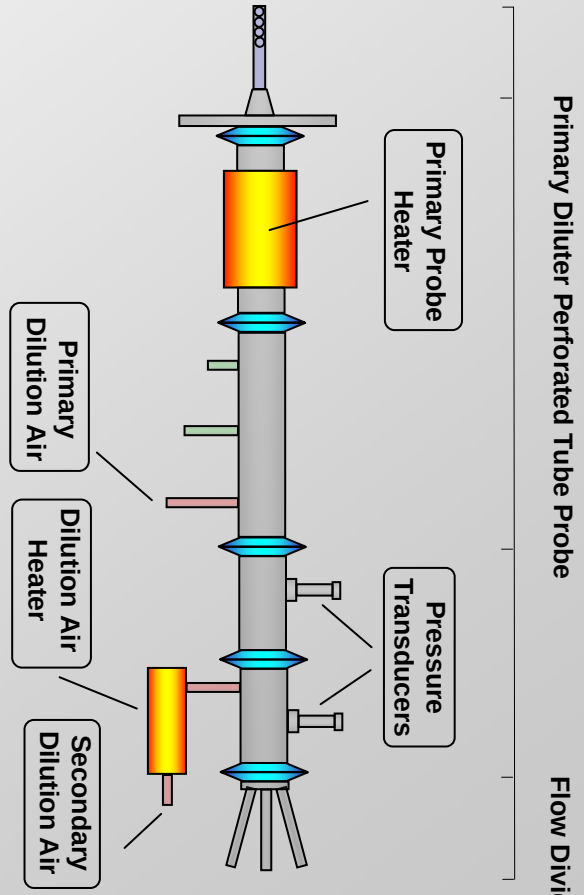
GM-CRL 1.9L SCE

- GM 1.9L SCE (0.47 L) w/ Re-entrant Bowl
- Bore x Stroke: 82.0 mm x 90.4 mm
- 16.1:1 CR
- High speed diesel
- BOSCH CP3.3 Pump w/ CRIP2 Injector
  - 143° Spray Angle
  - 7 holes
  - 1800 Bar Rail Pressure
  - Up to 5 injections per cycle
- Capability to >70% EGR (8% O_2)
- Currently used for LTC research

Dilution Conditions

- Two Stage Dilution
  1) Perforated tube
  2) Ejector diluter
- PDT: ~Isothermal
- SDT: 100 ±4 °C

Case	PDT	SDT	PDR	SDR	TDR
1 - Conv, 10.25 bar IMEP, Hi RP	215 ±5 °C	100 ±4 °C	4.7	7	33
2 - Conv, 5.5 bar IMEP, Hi RP	120 ±5 °C	100 ±4 °C	3.6	7	25
3 - PCI, 5.5 bar IMEP, Hi RP	100 ±5 °C	100 ±4 °C	3	7	21
4 - PCI, 5.5 bar IMEP, Lo RP	100 ±5 °C	100 ±4 °C	2.8	7	20



Other Measurement Considerations

- Steady state engine and sampling systems
- Insulated stainless steel transfer lines
- Filter face temperatures controlled to 47°C-50°C
- Exhaust gas sample underwent gradual decrease in temperature until capture and measurement
- Flow rate (filter face velocity) monitored during sampling
- Exhaust sampling point pressure controlled to 3 psig
- Checked variations in filter holder position

Engine Operating Conditions

Case	Engine Speed [RPM]	IMEP [bar]	Rail Press. [bar]	Inj. Timing [dATDC]	O2 Intake [%]	In. Tank T [°C]	In. Tank P [kPa_g]	Exh. Tank T [°C]	Exh. Tank P [kPa_g]
1	2500	10.25	1160	-12.8	16.3	64	83	435	105
2	2500	5.5	1160	-12.8	15.6	64	83	270	102
3	2500	5.5	1160	-38.5	9.7	65	68	270	84
4	2500	5.5	650	-38.5	8.7	65	66	270	81

Case 1 (Conv) :

- Medium Speed
- High Load
- High Injection Pressure
- Normal Injection Timing
- 30% EGR

Case 2 (Conv) :

- Medium Speed
- Medium Load
- High Injection Pressure
- Normal Injection Timing
- 50% EGR

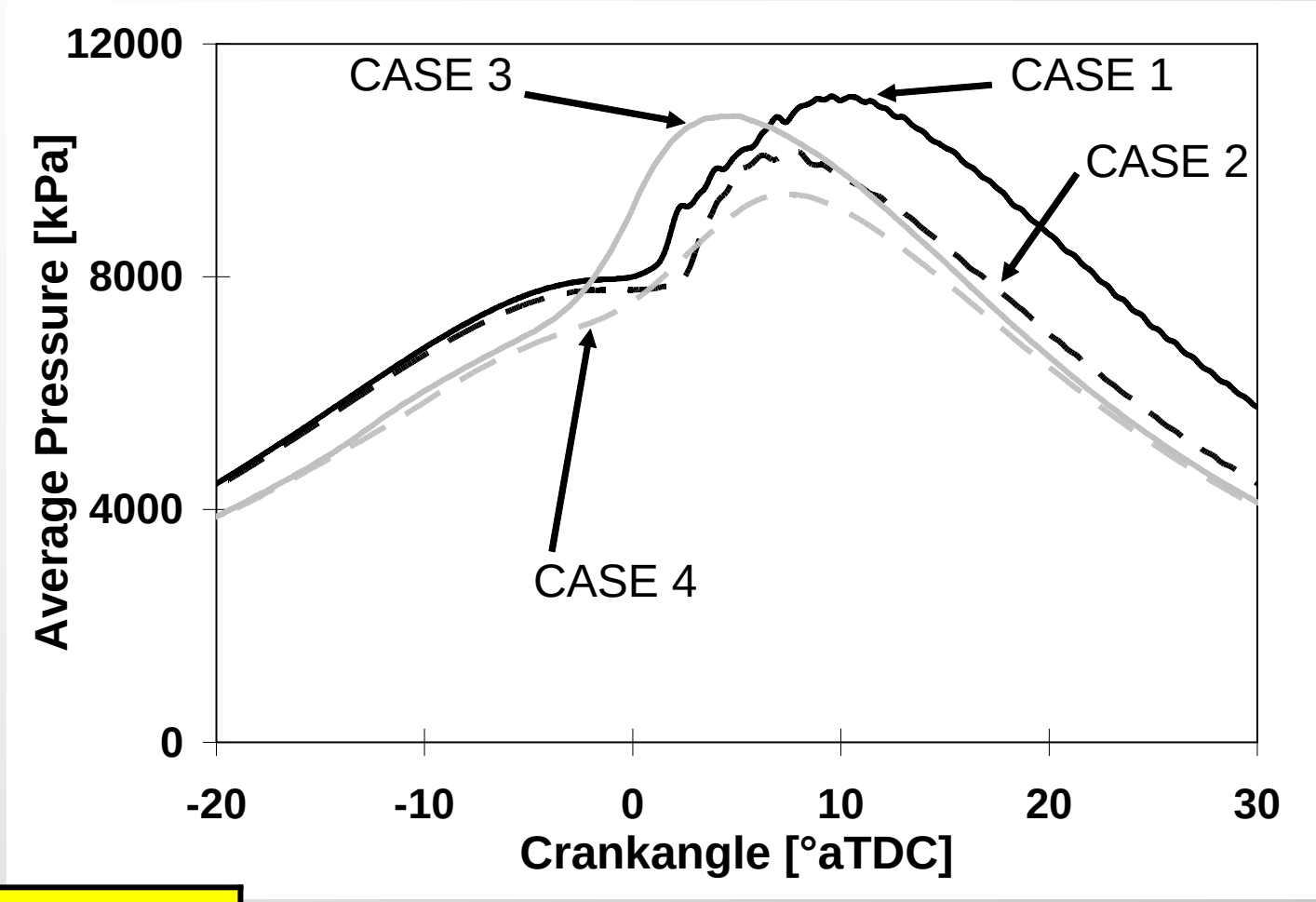
Case 3 (LTC) :

- Medium Speed
- Medium Load
- High Injection Pressure
- Early Injection Timing
- 60% EGR

Case 4 (LTC) :

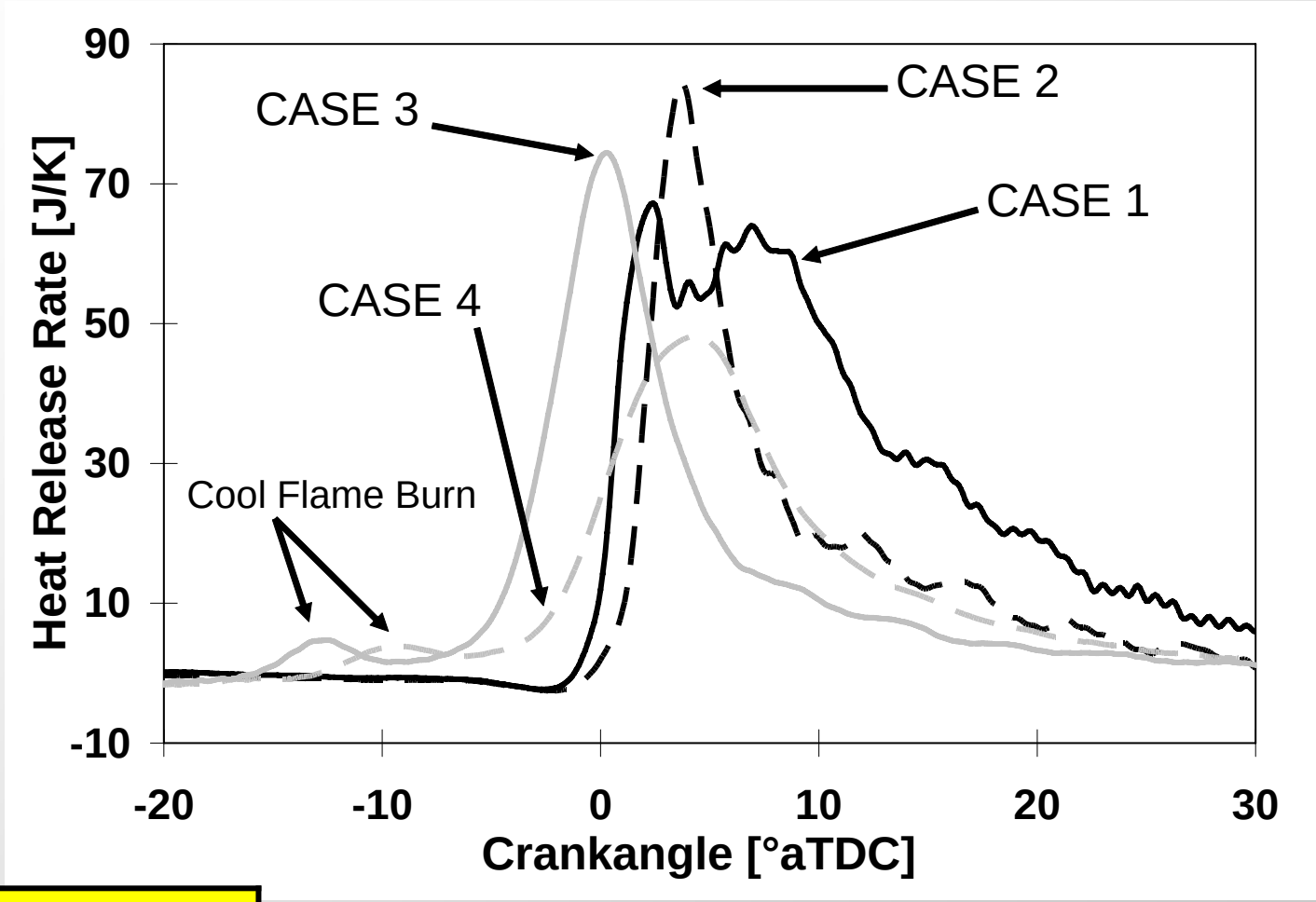
- Medium Speed
- Medium Load
- Low Injection Pressure
- Early Injection Timing
- 65% EGR

Pressure Trace



1	Conv. High Load
2	Conv. Med. Load
3	LTC High Inj. Pressure
4	LTC Low Inj. Pressure

Heat Release Rate



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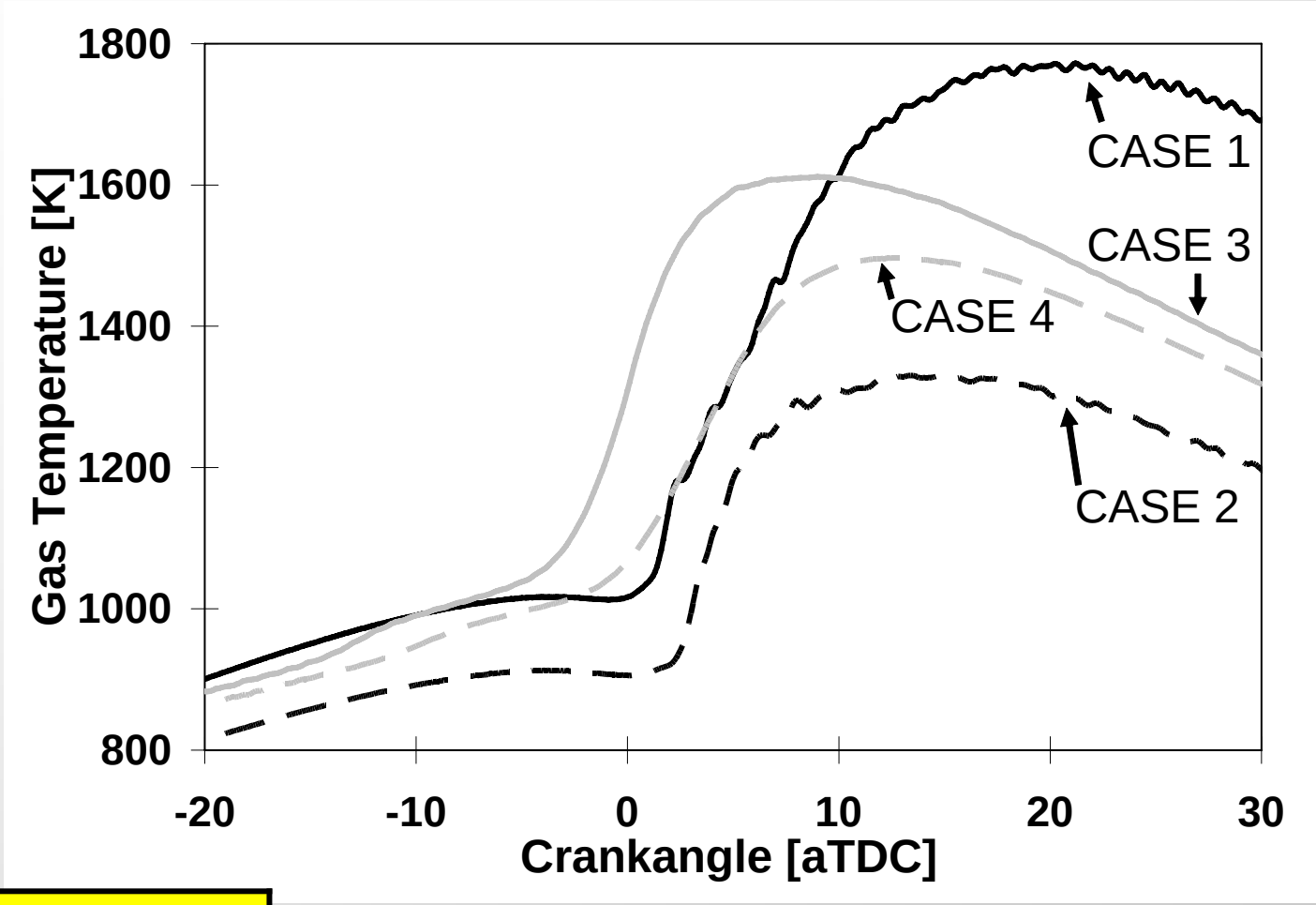
In-Cylinder Gas Temperature



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Gaseous Emissions

Case	Engine Speed [RPM]	IMEP [bar]	Rail Press. [bar]	Inj. Timing [dATDC]	O2 Intake [%]	In. Tank T [°C]	In. Tank P [kPa_g]	Exh. Tank T [°C]	Exh. Tank P [kPa_g]
1	2500	10.25	1160	-12.8	16.3	64	83	435	105
2	2500	5.5	1160	-12.8	15.6	64	83	270	102
3	2500	5.5	1160	-38.5	9.7	65	68	270	84
4	2500	5.5	650	-38.5	8.7	65	66	270	81

Case	Unburned HC [g/kg_fuel]	NOx [g/kg_fuel]	H2 [g/kg_fuel]	O2 [g/kg_fuel]	CO [g/kg_fuel]	CO2 [g/kg_fuel]
1	0.92	4.44	0.13	1431.57	7.45	3169.31
2	1.28	2.47	0.11	3019.43	5.99	3149.28
3	5.01	0.07	2.27	564.14	120.97	2956.80
4	19.95	0.06	9.74	410.42	452.46	2388.58

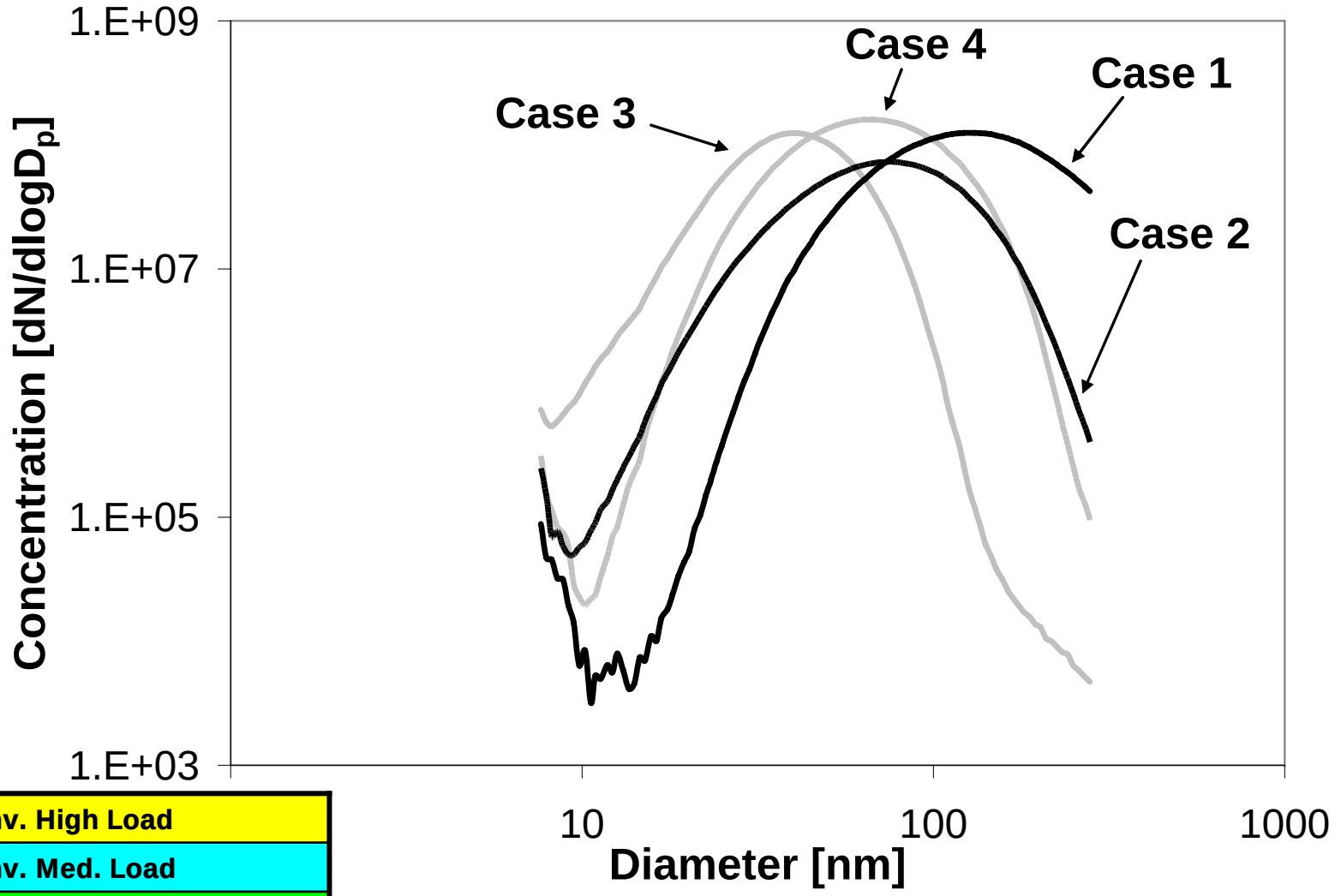
Case 1 – Lowest HC and CO. Highest NOx and CO2.

Case 2 – Low HC and CO. High NOx and O2.

Case 3 – Low NOx and O2. High HC and CO.

Case 4 – Low NOx and O2. Highest HC, CO, and H2.

SMPS Size Distribution



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Size and Mass Statistics

Case	1	2	3	4
Total Number Conc. [#/cc] x10^9	4.05	2.42	3.12	5.08
Geometric Mean Particle Diameter [nm]	120	70.3	38.8	64.6
Mode Diameter [nm]	126	76	40	69
Teflon Filter Mass [g/kg_fuel]	2.4	0.39	0.08	0.47

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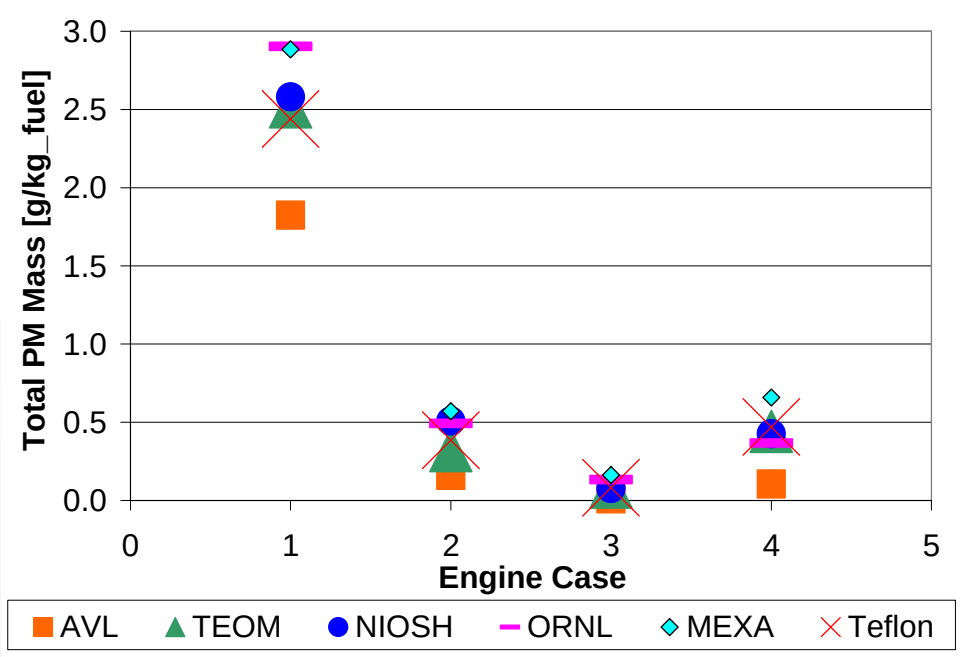
Total PM Mass Emissions Index



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Instruments:

AVL Smoke Meter 415S – Paper Opacity

TEOM – R&P Tapered Element Oscillating Microbalance

NIOSH - Sunset Laboratories Carbon Analyzer by NIOSH 5040 Method with Tissuquartz filters

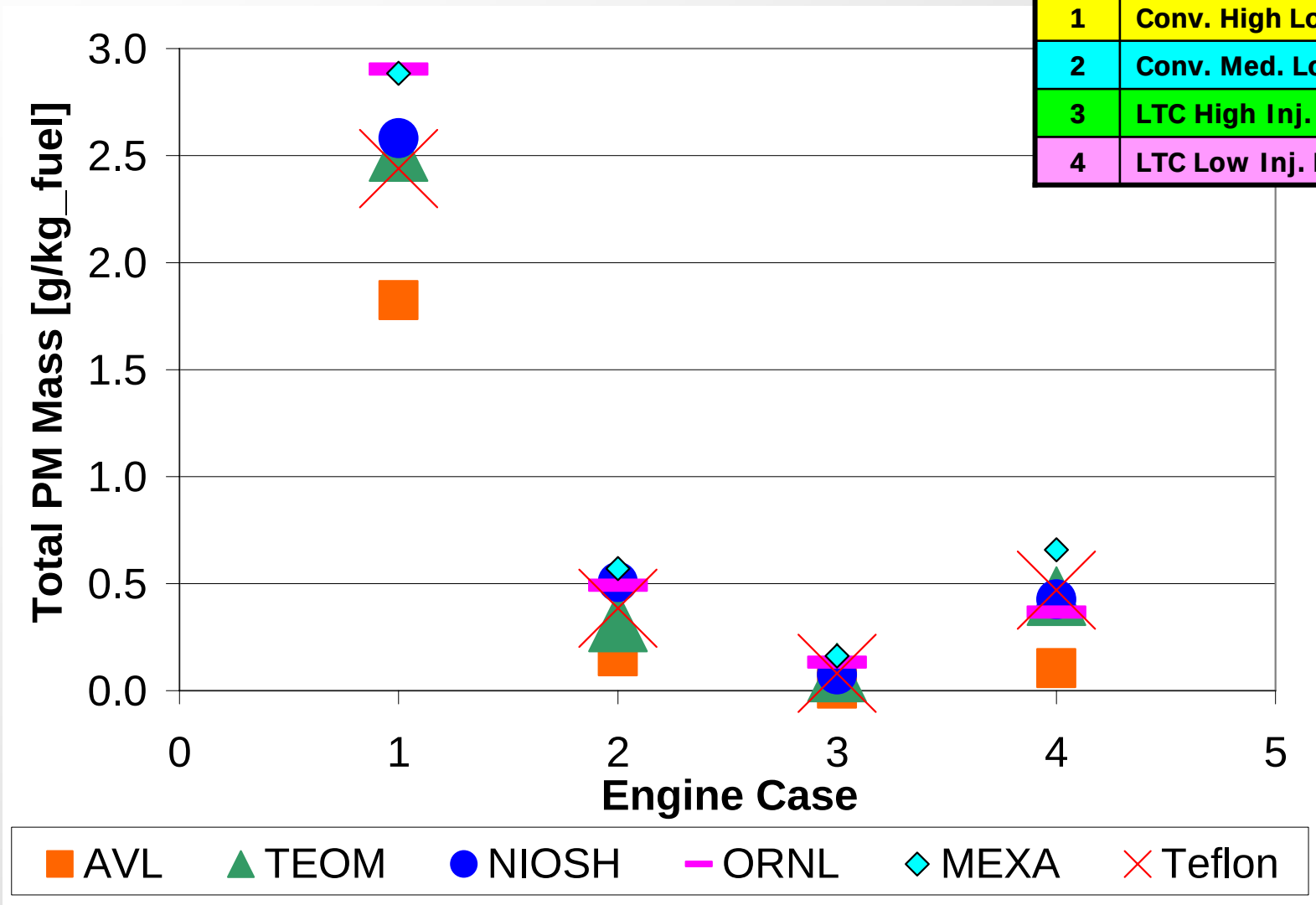
ORNL – Oak Ridge National Lab TX40 Gravimetric Analysis

MEXA – Horiba MEXA 1370PM with Tissuquartz filters

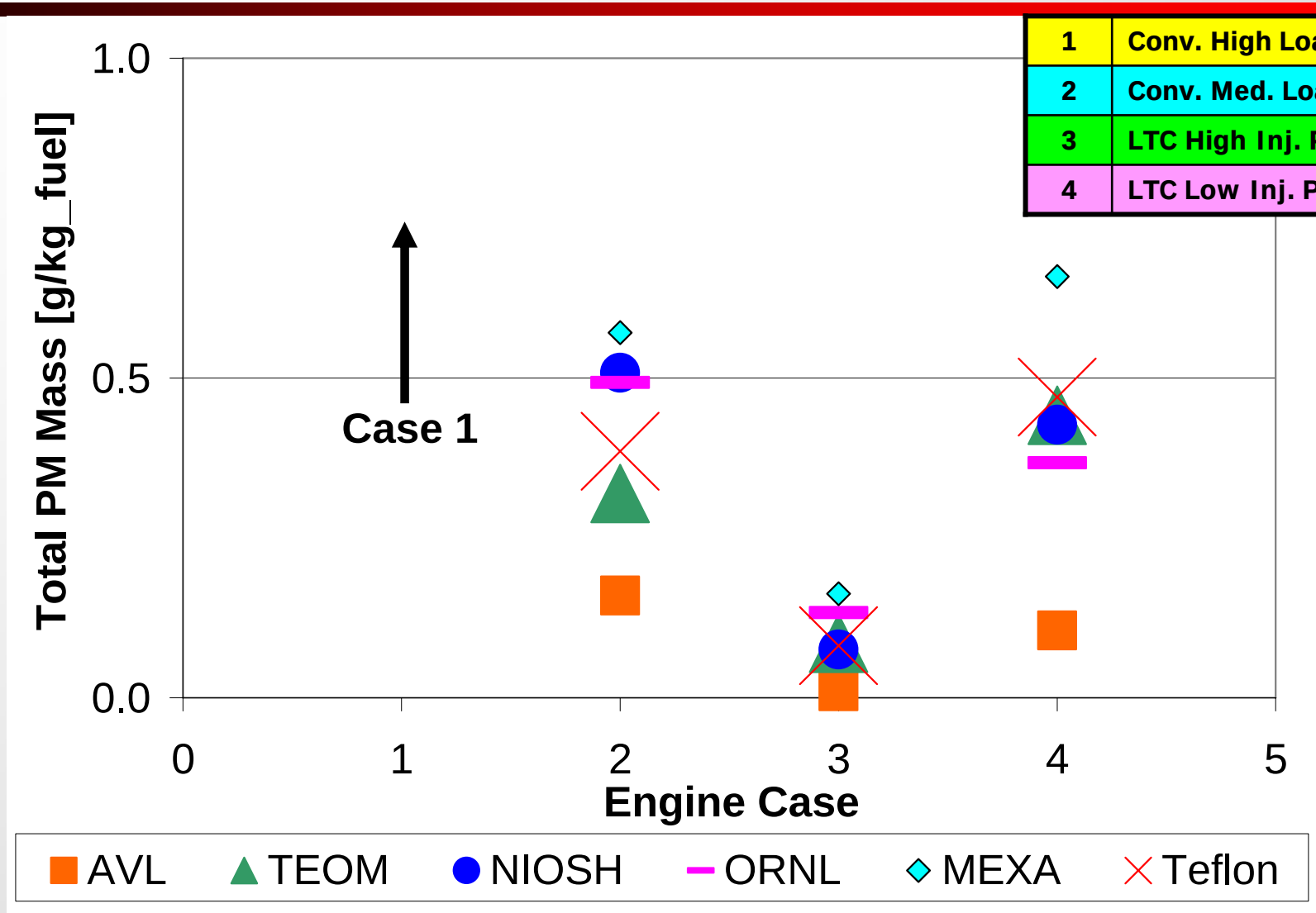
Teflon – Gravimetric Analysis

MICRO – Oak Ridge National Lab TX40 SOF Microwave Extraction

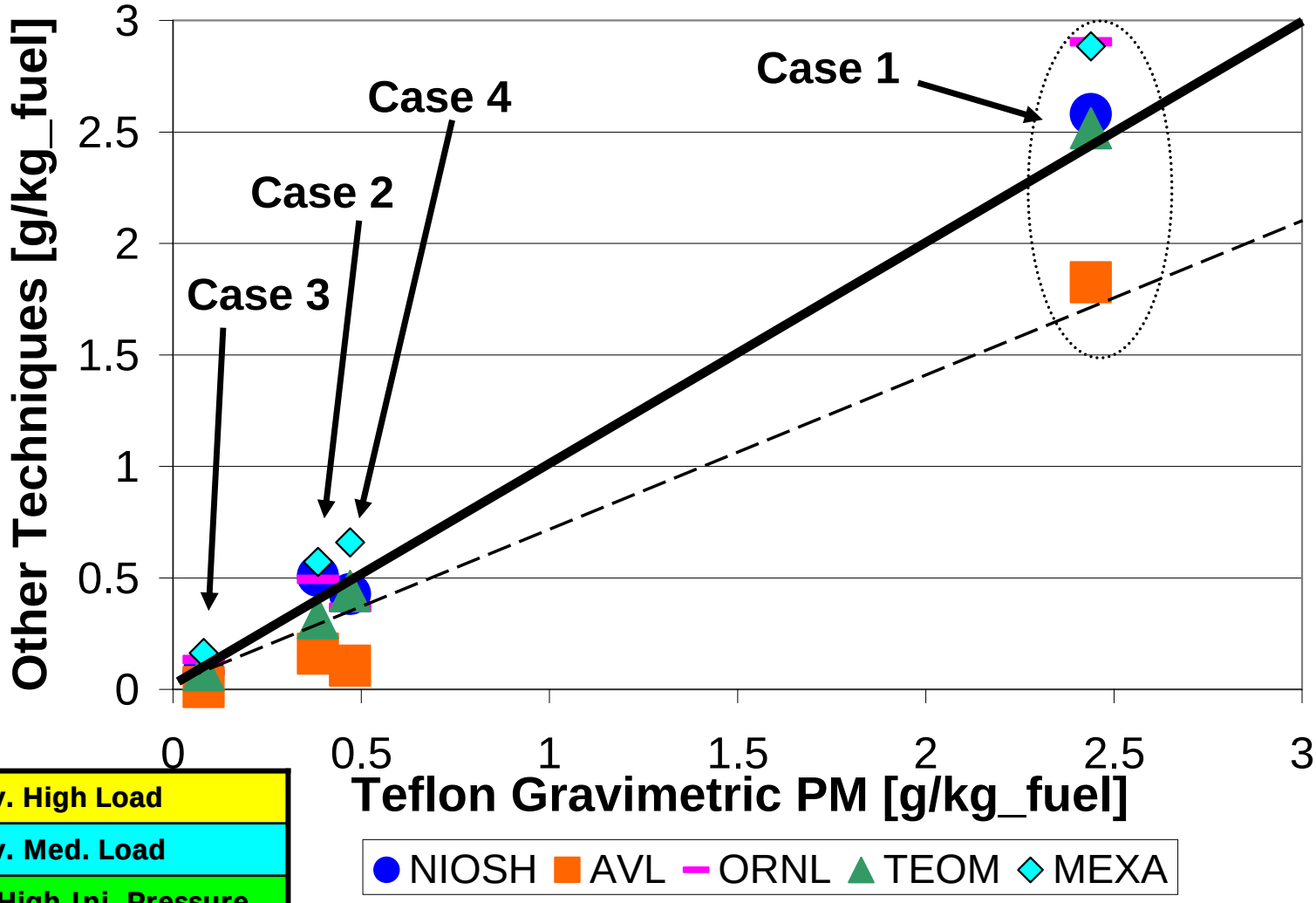
Total PM Mass Emissions Index



Total PM Mass Emissions Index (zoom)



Teflon Gravimetric Comparison



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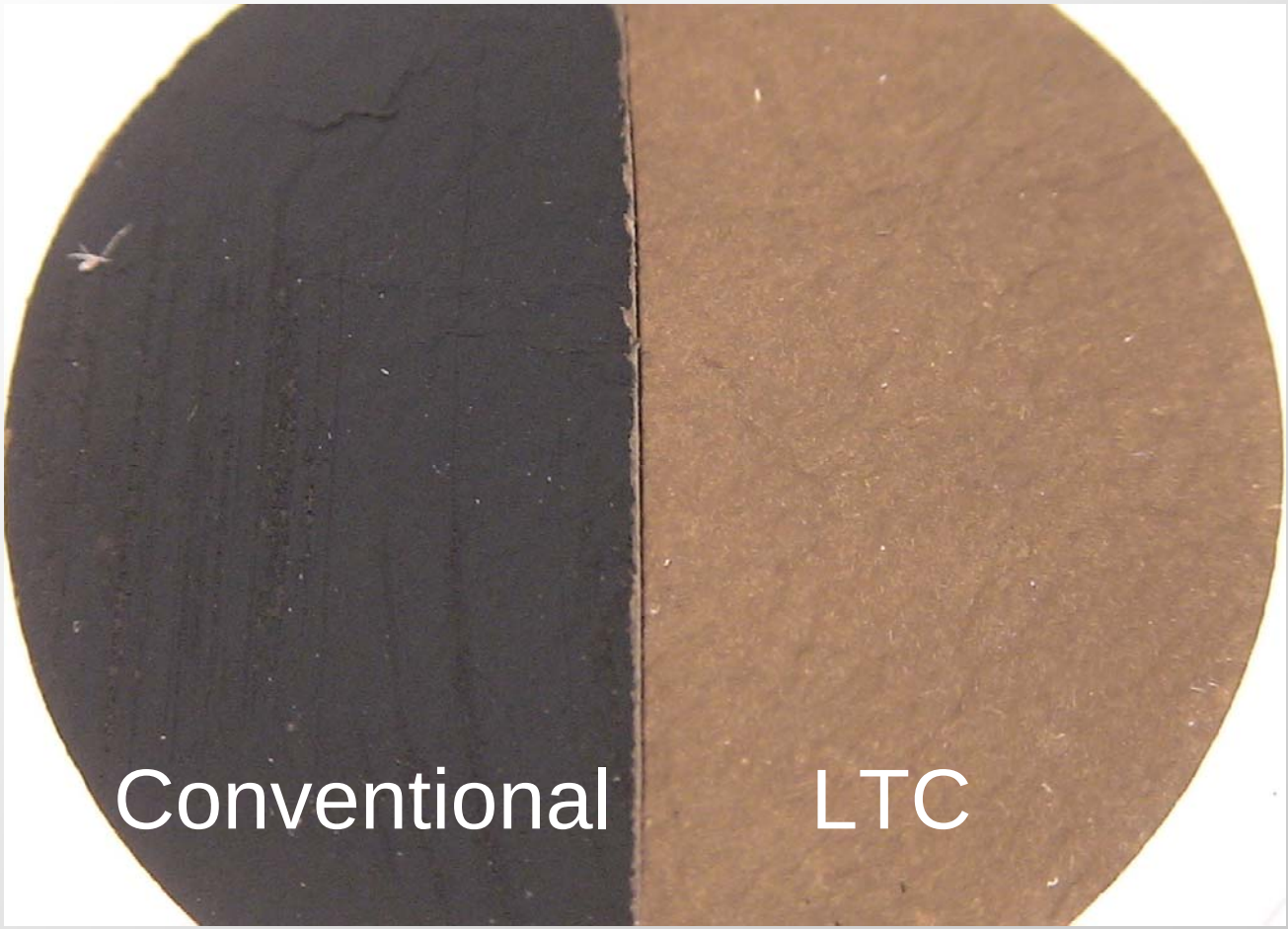
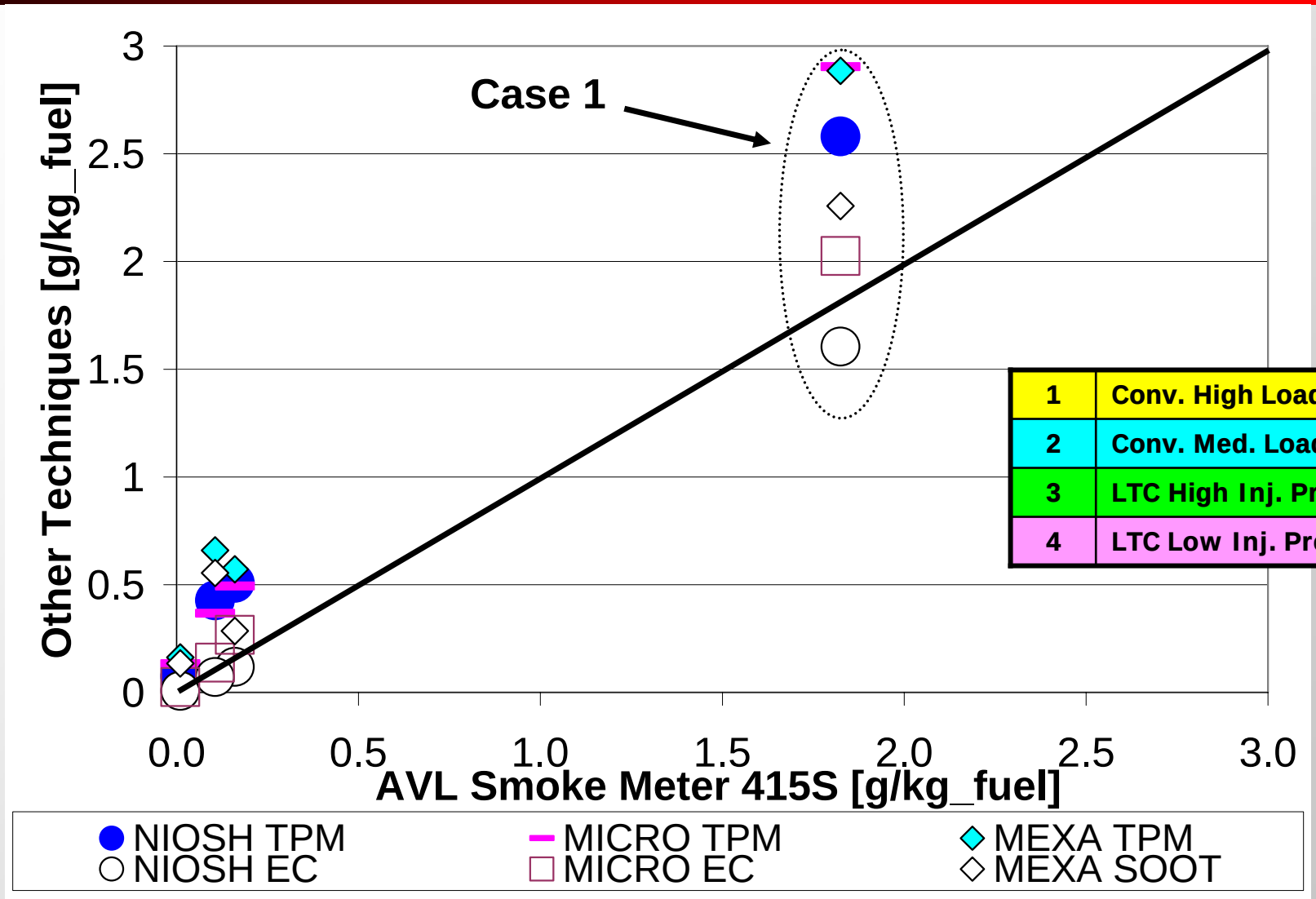
Filter Analysis



Color difference between PM from Conventional and LTC diesel combustion

Elemental Carbon Comparison



Filter Artifact Correction

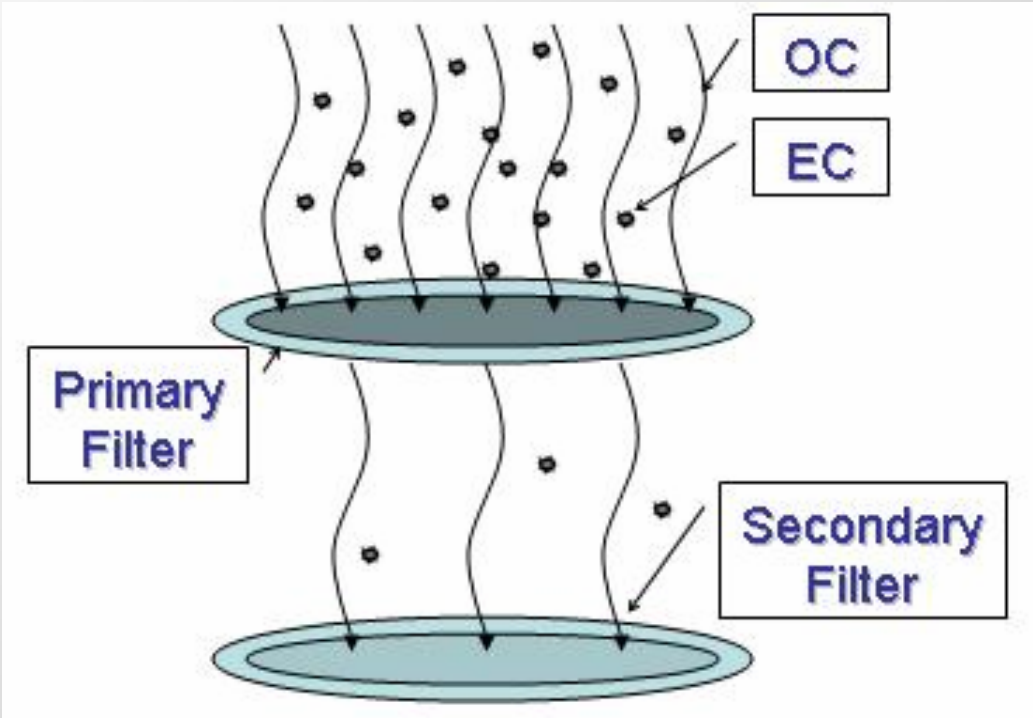
OC Correction

$$OC_{Final} = OC_{Primary} - OC_{Secondary}$$

EC Correction

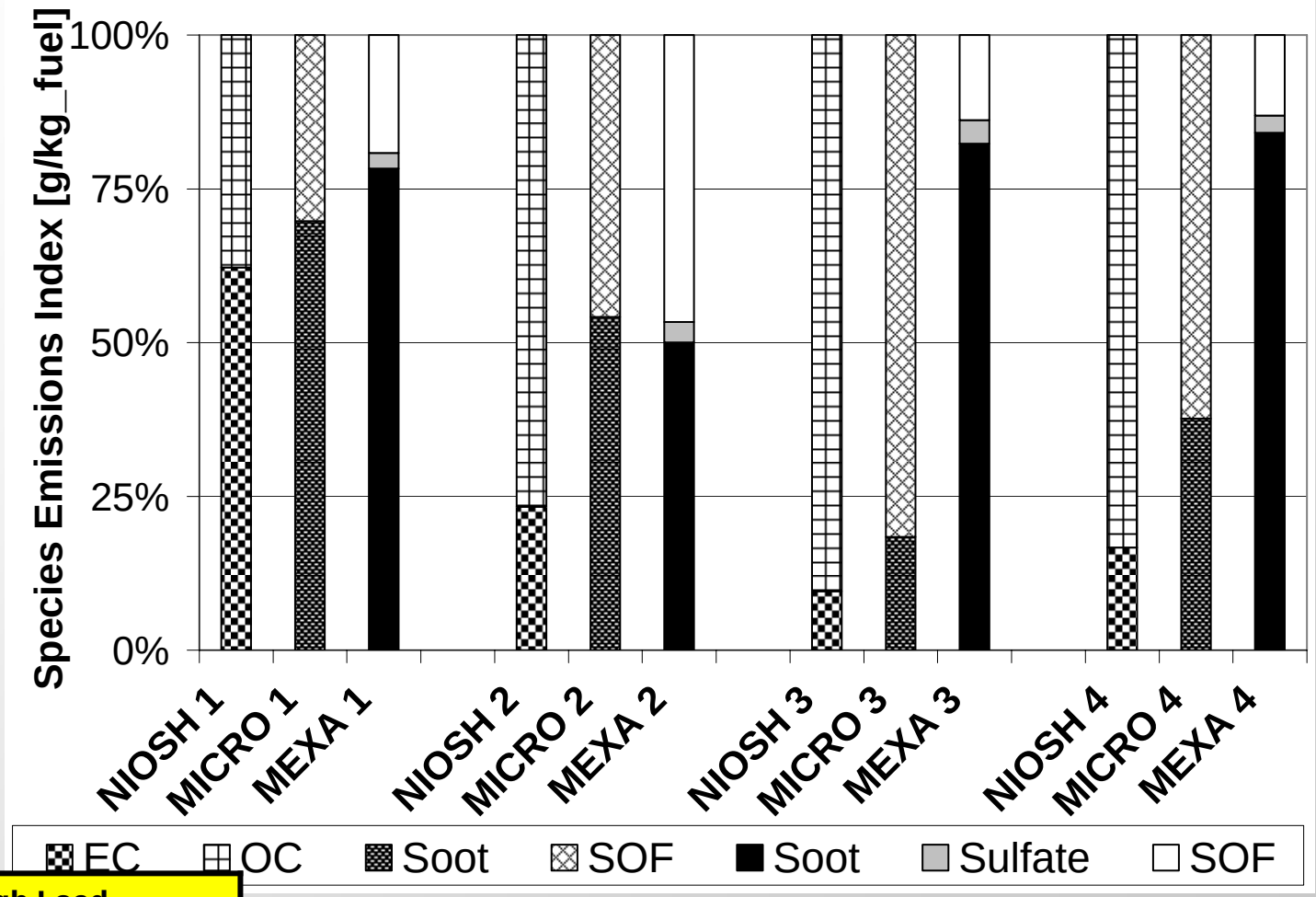
$$EC_{Final} = EC_{Primary} + EC_{Secondary}$$

At this time, only the NIOSH and MEXA filters were artifact corrected.



Normalized Chemical Speciation

(Artifact Corrected, Except MICRO)



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Organic Analysis

Case	1	2	3	4
Unburned HC [g/kg_fuel]	**.92**	**1.28**	**5.01**	**19.95**
Maximum Combustion Temperature [K]	1772	1330	1612	1497
Combustion Efficiency [%]	99.7	99.6	96.5	**85.5**
NIOSH OC [%]	**38**	**77**	**90**	**83**
Microwave Extracted SOF [%]	34	44	**80**	59
MEXA SOF [%]	19	48	13	15

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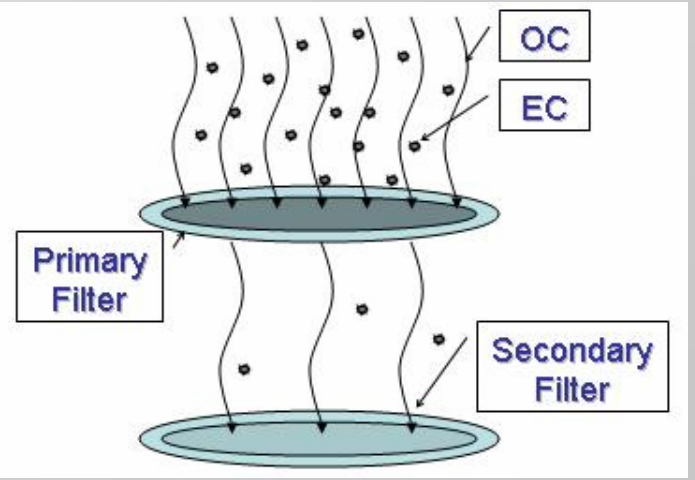
Artifact Magnitude

EC Artifact Magnitude

$$EC\ Artifact = 100 \times EC_{Secondary} / (EC_{Primary} + EC_{Secondary})$$

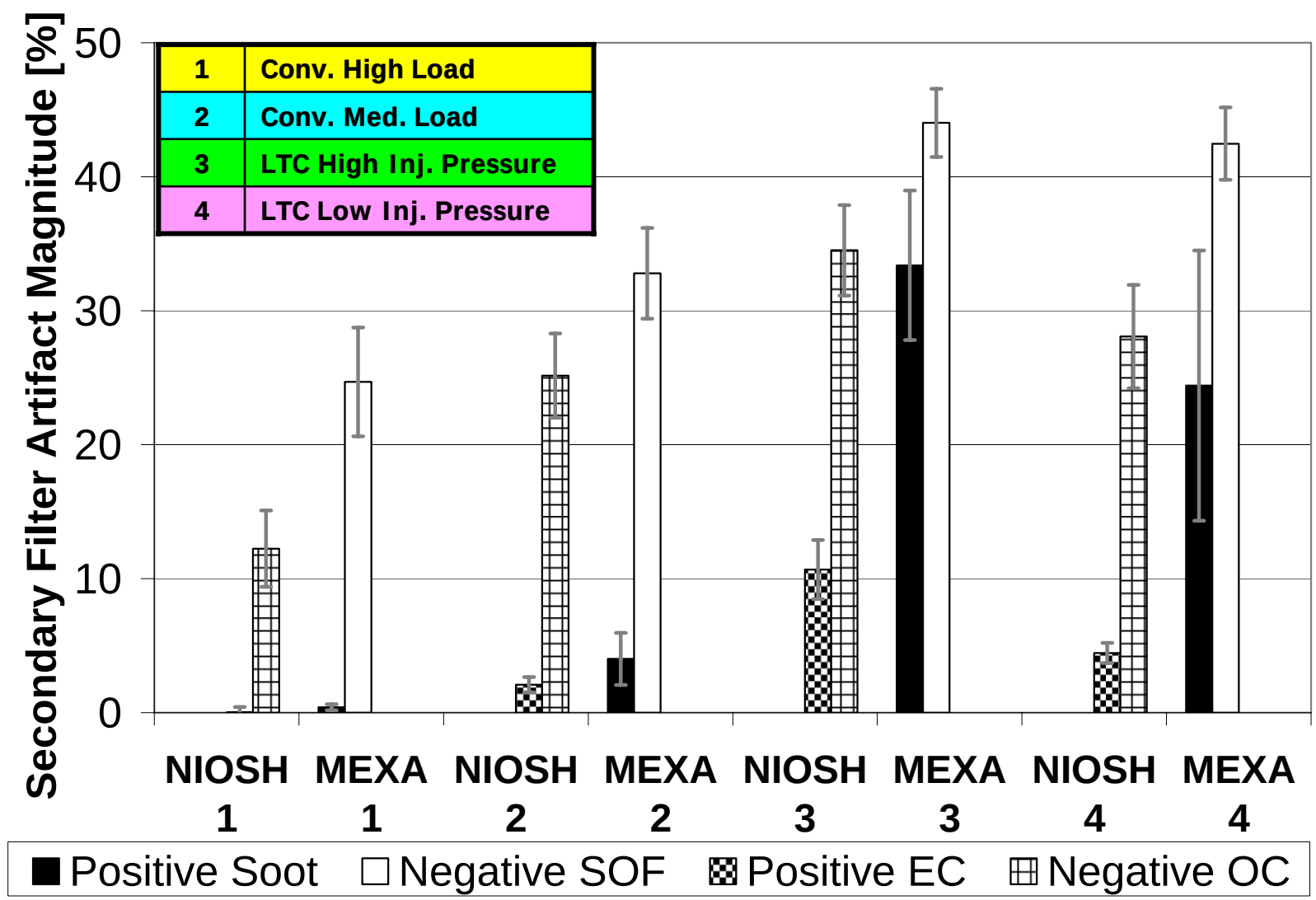
OC Artifact Magnitude

$$OC\ Artifact = 100 \times OC_{Secondary} / (OC_{Primary} + OC_{Secondary})$$



Artifact Magnitudes

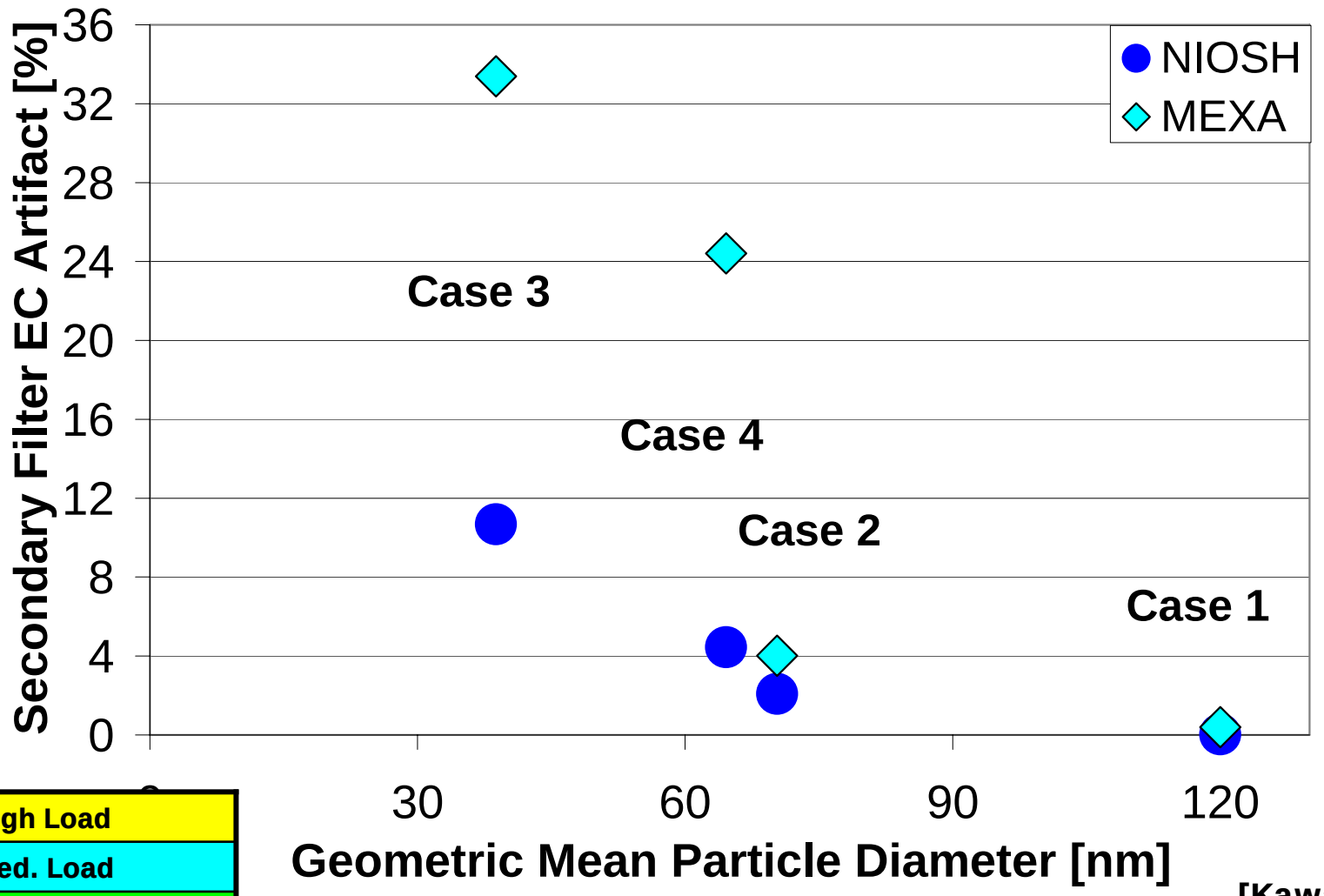
Why the high EC on secondary filters for Cases 3 and 4?



High EC Positive Artifact in Cases 3 & 4

- OC is being counted as EC during the transition from the OC measurement stage to EC measurement stage?
- EC is at minimum detection limit of instruments?
- OC is darker than conventional cases? (NIOSH laser uncertainty)
- New type of smaller particles aren't being filtered as well?

EC Artifact Compared to Particle Size



[Kawai]

1	Conv. High Load
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LTC and Conventional PM Differ

- Accumulation mode occurs at smaller particle sizes
- Very low PM concentrations
- High organic content
- High HC emissions do not track with adsorbed OC
- High EC positive artifact

Conclusions

- Same trends found among different instruments
- Low concentrations and higher OC content proved more difficult to measure
- AVL 415S tracks most closely with EC
- Artifact correction(s) are necessary to accurately assess total PM
- LTC and Conventional PM have very different concentrations, chemical composition, and size distributions