X-ray Based Techniques for Transportation Applications

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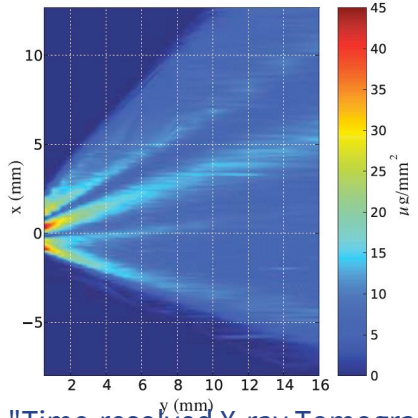
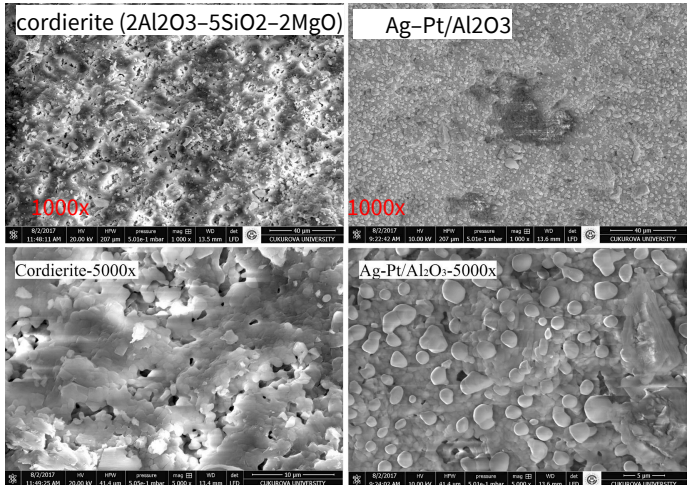
OVERVIEW

X-ray diagnostics are widely used to characterize inner structure of high pressure **fuel injection systems**:

- X-ray radiography/tomography provides quantitative measurements of density in variable-density flows.
- X-ray phase-contrast imaging is used to visualize multiphase flows with high spatial and temporal resolution.



Duke, D. et al., "Time-resolved X-ray Tomography of Gasoline Direct Injection Sprays," SAE Int. J. Engines 9(1):2016, doi:10.4271/2015-01-1873.



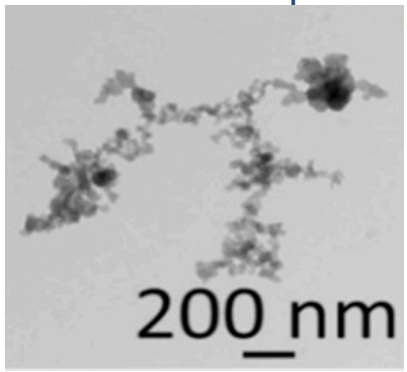
Internal structure, Inhibition, Poisoning of **engine exhaust catalyst**:

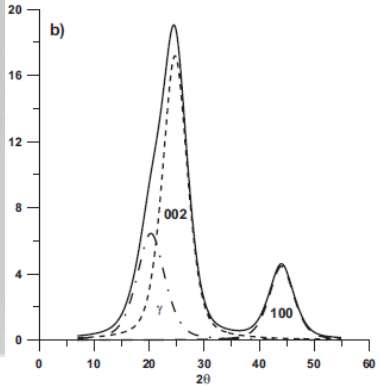
- Scanning electron microscopy (SEM) provides structure information
- XRF gives an insight on the elements and compounds
- XRD determines the crystalline structure of catalyst

Resitoglu et al. Selective catalytic reduction of NOx emissions by hydrocarbons over Ag–Pt/Al2O3 catalyst in diesel engine. Int. J. Environ. Sci. Technol. 16, 6959–6966 (2019).

Engine exhaust Soot structure, agglomeration:

- Scanning (SEM) and Transmission (TEM) electron microscopy provide structure information
- XRF accounts for embedded species
- XRD determines the crystalline structure of particles

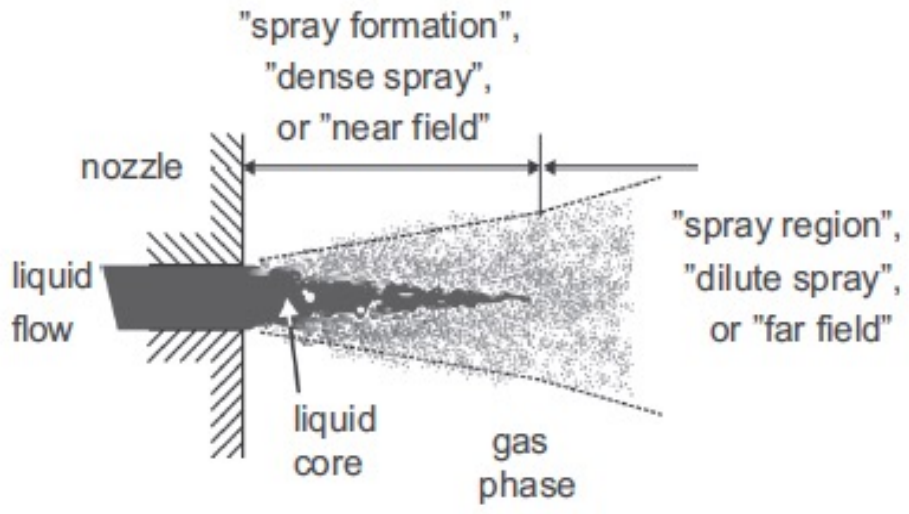




Lapuerta, M., et al. (2020). Soot reactivity analysis and implications on diesel filter regeneration. Progress in Energy and Combustion Science, 78, 100833.

X-RAY IMAGING OF FUEL SPRAYS

How a high pressure spray works?



Sketch of the spray regions *

M. Linne, Imaging in the optically dense regions of a spray: a review of developing techniques, Progress in Energy and Combustion Science, 2013, 39: 403-440.

What has been done

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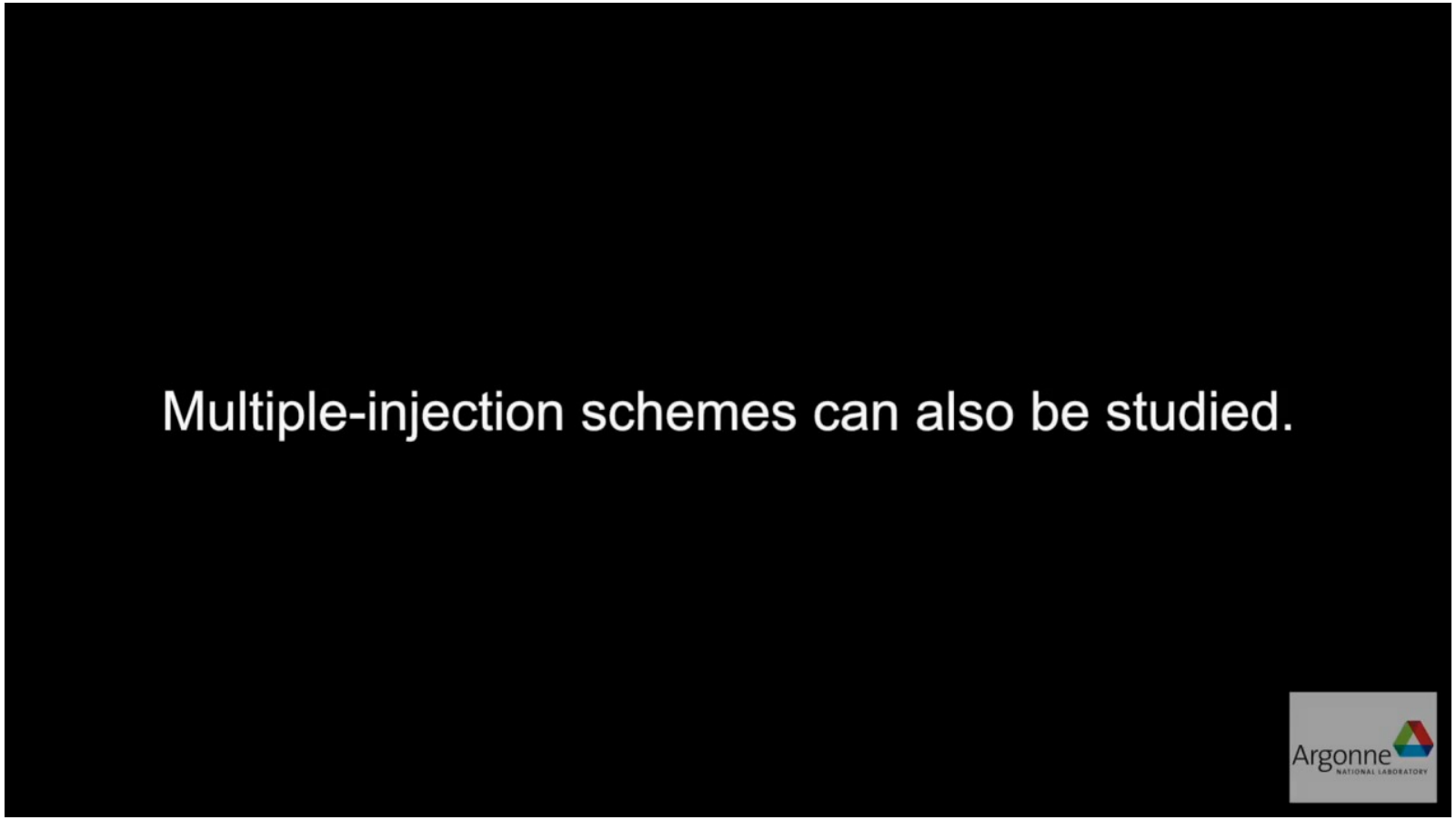
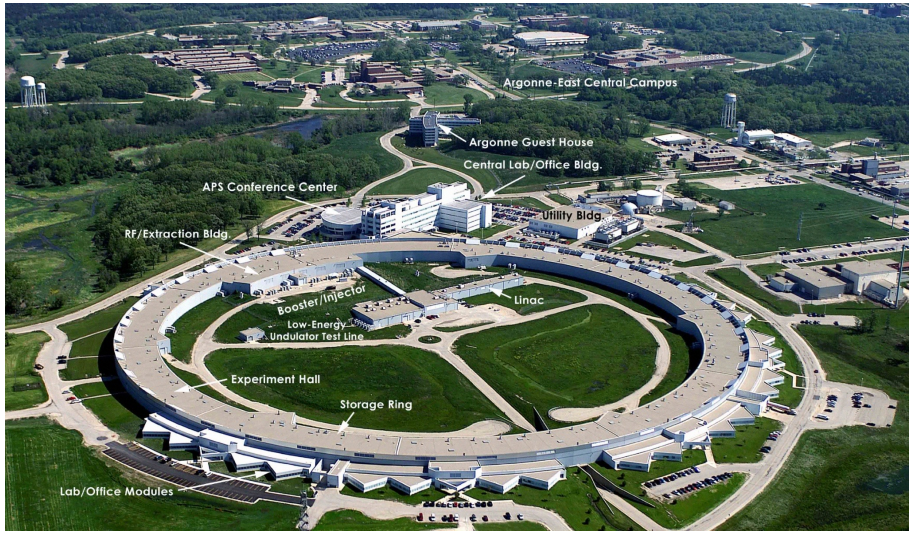
X-RAY IMAGING OF FUEL SPRAYS

Optical measurements about the internal structure of the spray results quite complicated, especially in the dense region close the nozzle

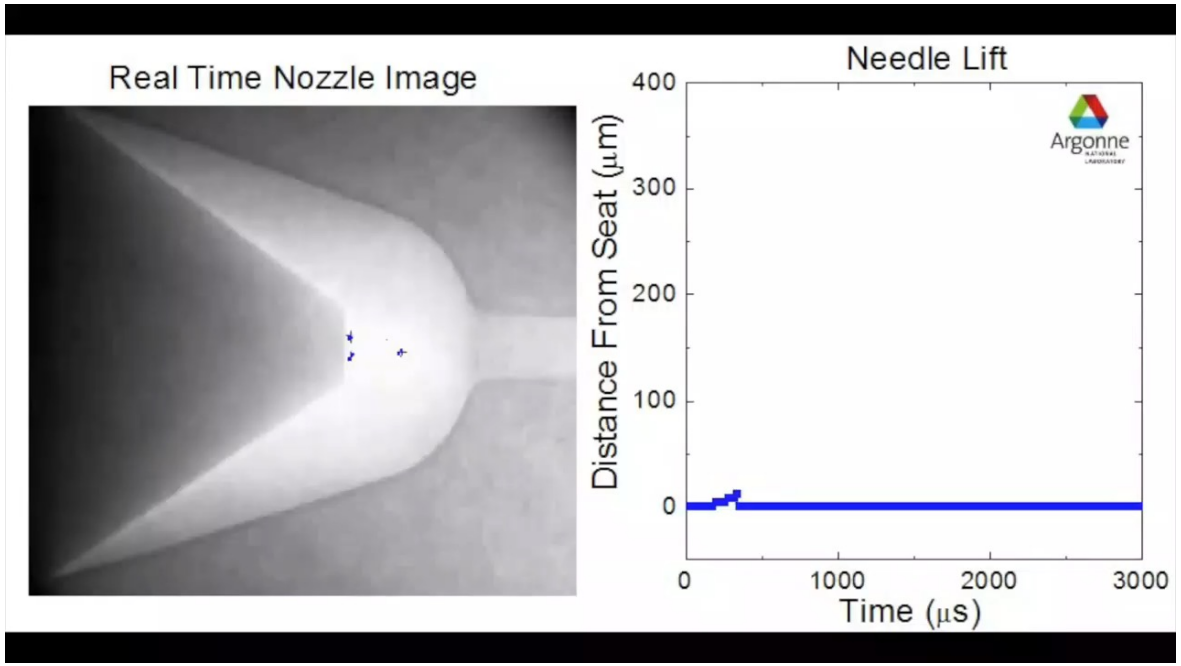
X-RAY IMAGING OF FUEL SPRAYS

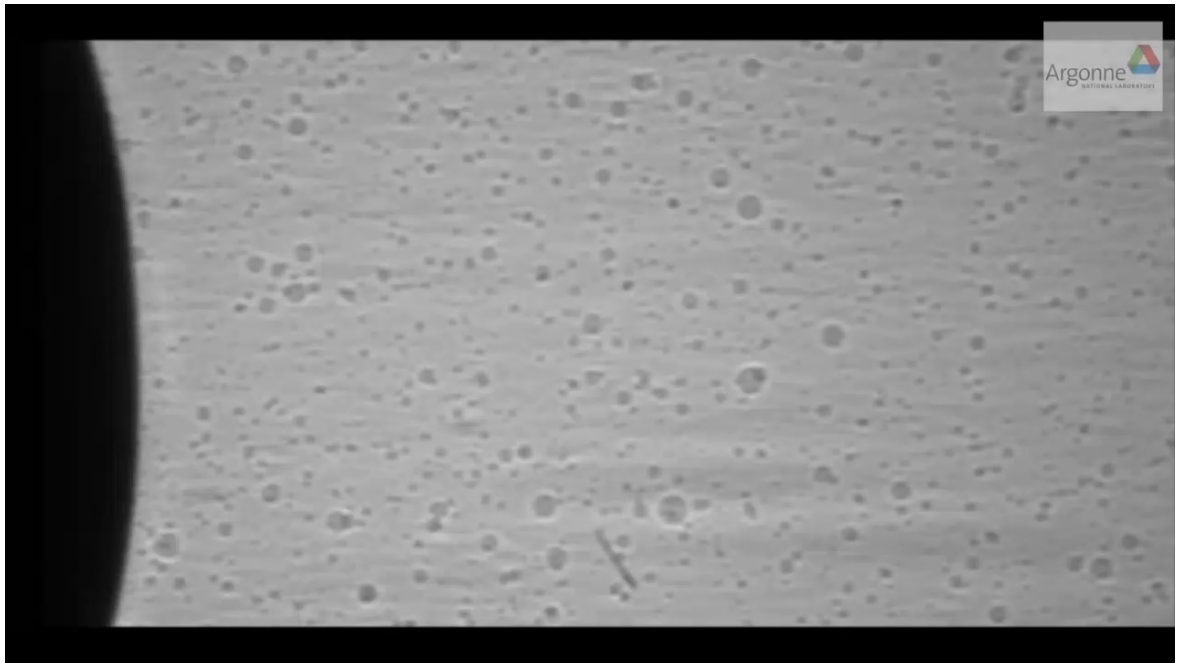




X-ray radiography and tomography can be applied to estimate the fuel distribution into high-density regions of fuel sprays.

X-RAY IMAGING OF FUEL SPRAYS

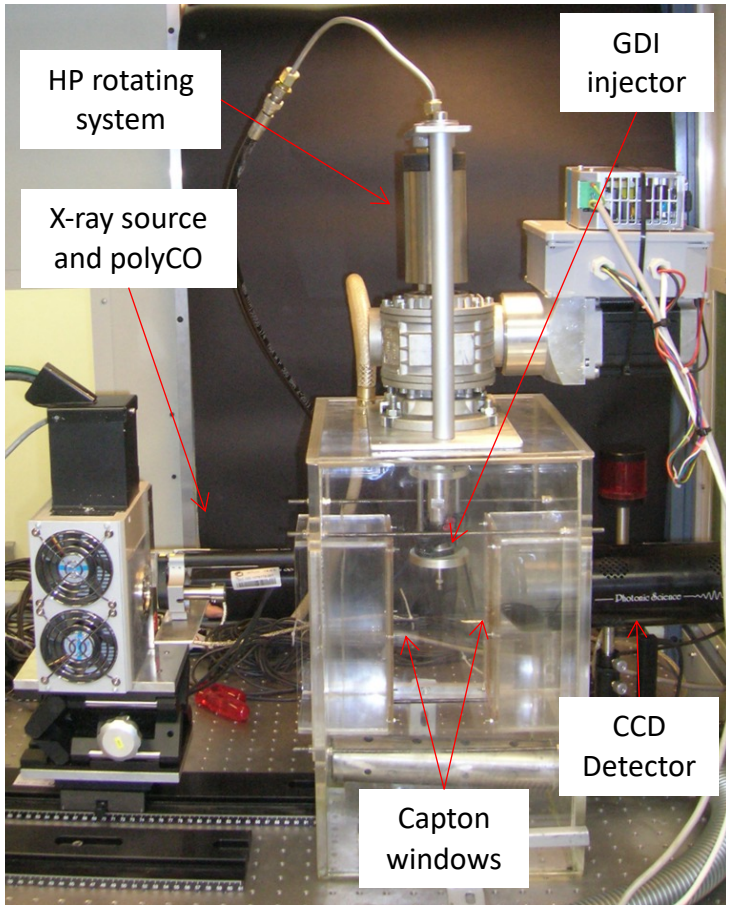


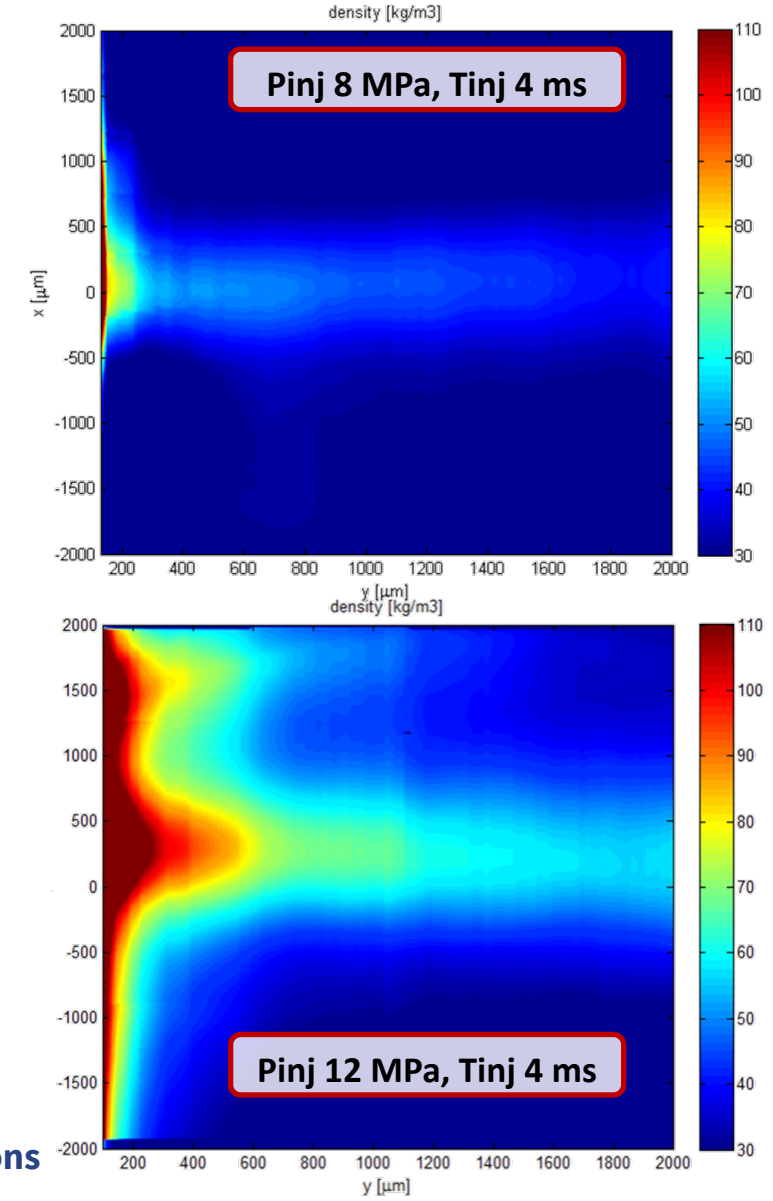


Phase contrast imaging allows time resolved acquisition of sprays inner structure

What we did

X-RAY TOMOGRAPHY IN LNF-INFN





Marchitto et al. “Quantitative measurements of GDI sprays through optical and x-ray based techniques.” Channeling 2016

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Engine exhaust Soot

X-RAY BASED TECHNIQUES FOR TRANSPORTATION APPLICATIONS

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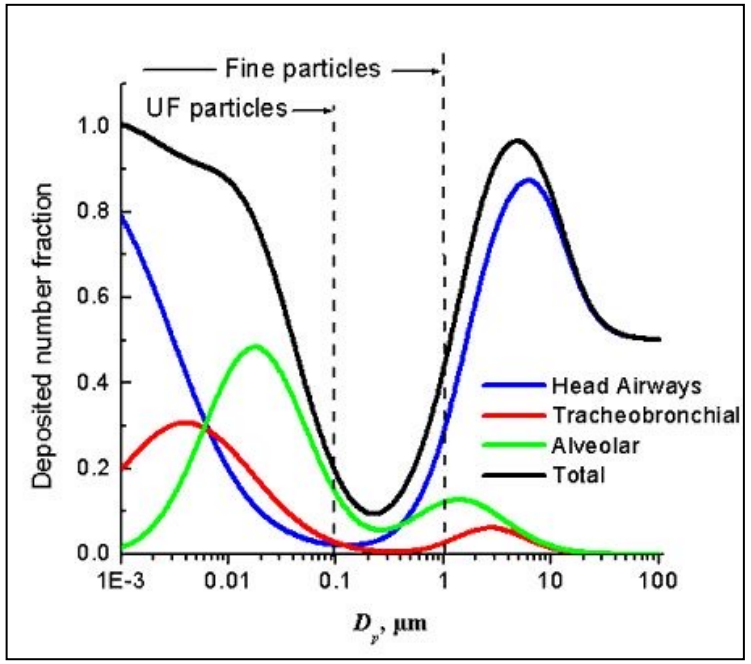
ENGINE EXHAUST SOOT



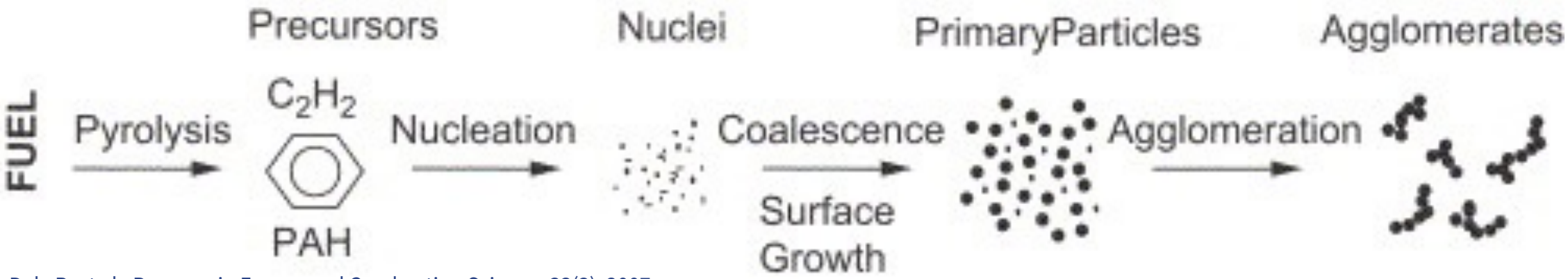
- Engine particulate matter (PM) emissions have been a major concern because of their ill-effects on human health.
- Soot particles form a major part of PM emissions

	Particle number (PN)	Particulate Mass (PM)
Euro 6	$6x10^{11}$ /km for particles larger than 23nm	4.5 mg/km
Euro 7	$6x10^{11}$ /km for particles larger than 10nm	4.5 mg/km

By 2025, new Euro 7 regulation will be focused on the reduction of particulate matter size.

ENGINE EXHAUST SOOT

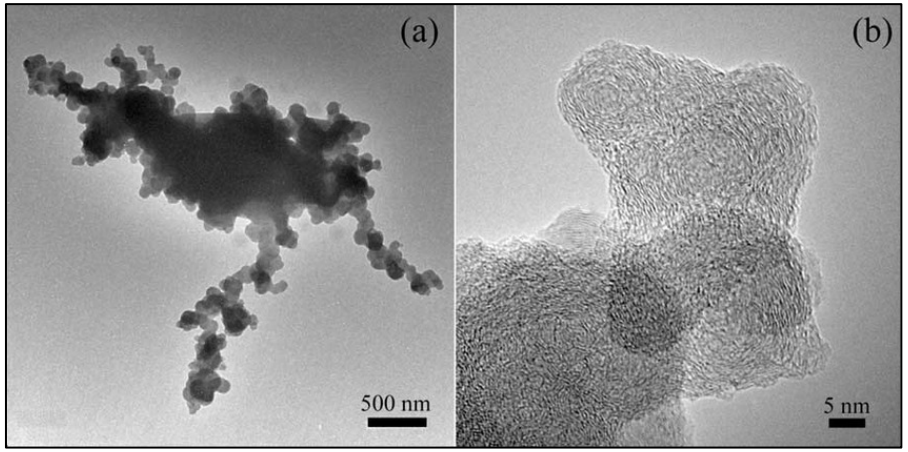
Soot formation



Dale R. et al., Progress in Energy and Combustion Science, 33(3), 2007

Soot structure

TEM images of a soot particle.
a) chain-like soot aggregate.
b) High-resolution TEM image of soot shows the onion-like structure of curved and disordered graphitic layers.



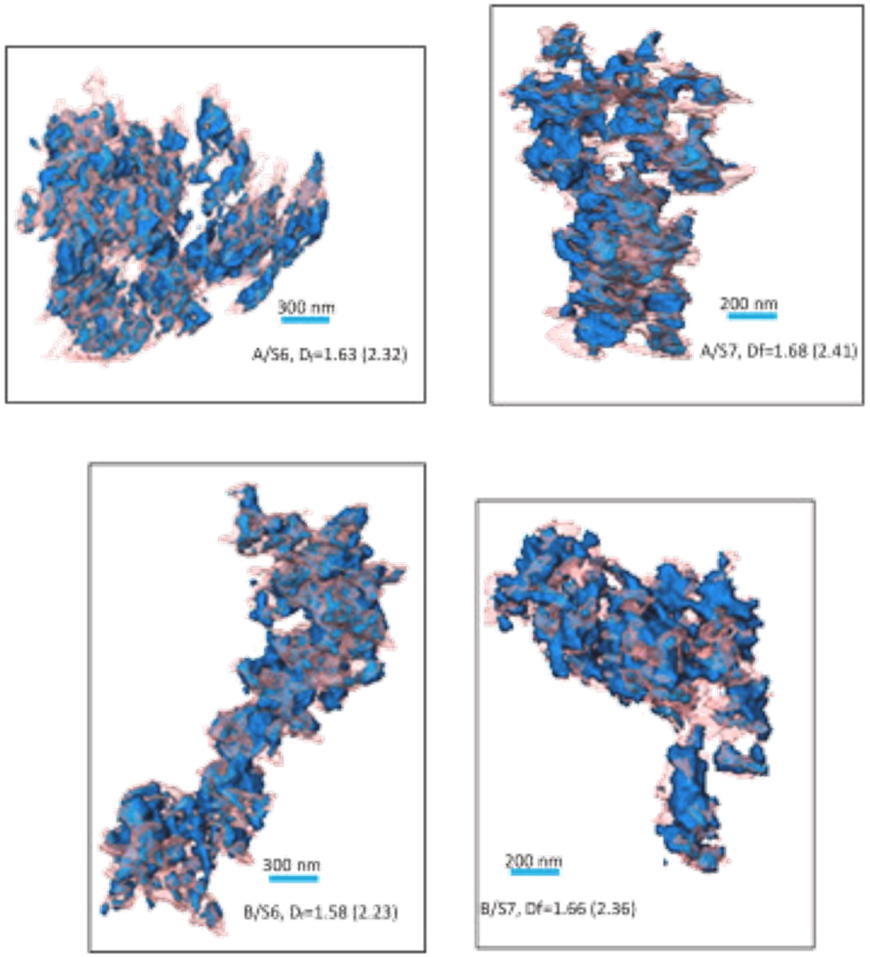
Li, W et al., Journal of Geophysical Research Atmospheres 114(9), 2009

ENGINE EXHAUST SOOT

X-ray tomography of soot

PM particle consists of two light intensity ranges with a light intensity ratio of 1.3 ± 0.1.

- More intense signal is ascribable to soot
- Lower intensity accounts for condensed volatile organic compounds (soot precursors).
- Soot fraction is characterized by cluster-like or chain-like agglomerates constituted by loosely attached aggregates.



Yan, F., Song, J., Zhuang, Y., Qiu, L., Li, Z., & Meng, Z. (2021). Three-dimension soft X-ray tomographic reconstruction of particulates emitted from a diesel engine. Journal of Aerosol Science, 156, 105784.

X-ray Diffraction of soot

A typical soot diffraction pattern provides a large background intensity, due to the amorphous carbon in the soot, and two bands.

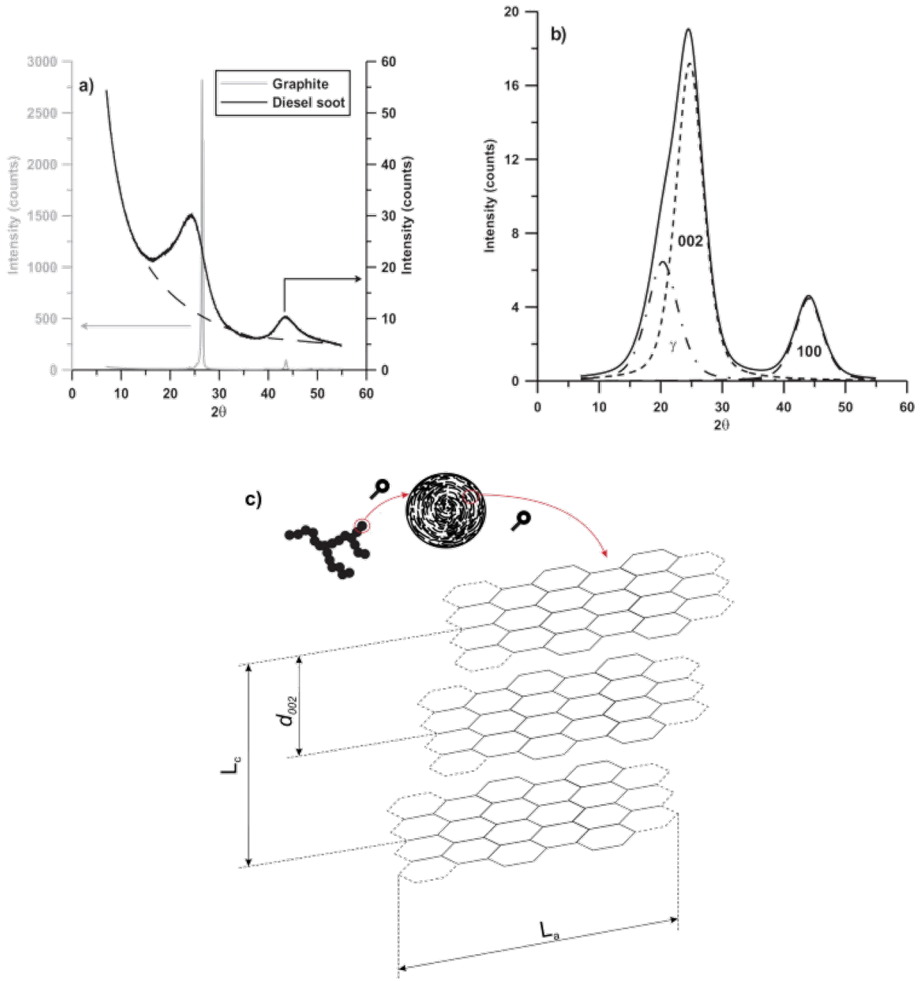
- The first band is located at a diffraction angle around 2θ = 25°
- the second band at 2θ = 43°.

X–ray diffraction provides information about the interplanar distance between graphene layers (d002) and the stacking thickness (Lc) and length of the crystallites (La).

$$d_{002} = \frac{n \cdot \lambda}{2 \cdot \sin \theta_{002}}$$

$$L_c = \frac{K_c \cdot \lambda}{\beta_{002} \cdot \cos \theta_{002}}$$

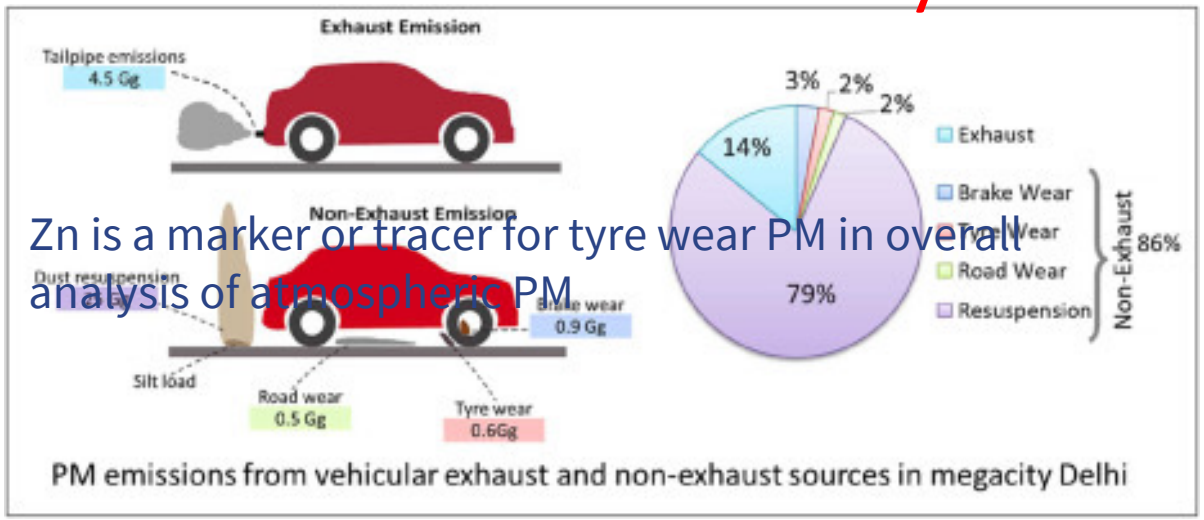
$$L_a = \frac{K_a \cdot \lambda}{\beta_{100} \cdot \cos \theta_{100}}$$



Lapuerta, M., Rodríguez–Fernández, J., & Sánchez-Valdepeñas, J. (2020). Soot reactivity analysis and implications on diesel filter regeneration. Progress in Energy and Combustion Science, 78, 100833.

TYRE AND ROAD WEAR PARTICLES

X-ray Diffraction of TRWP

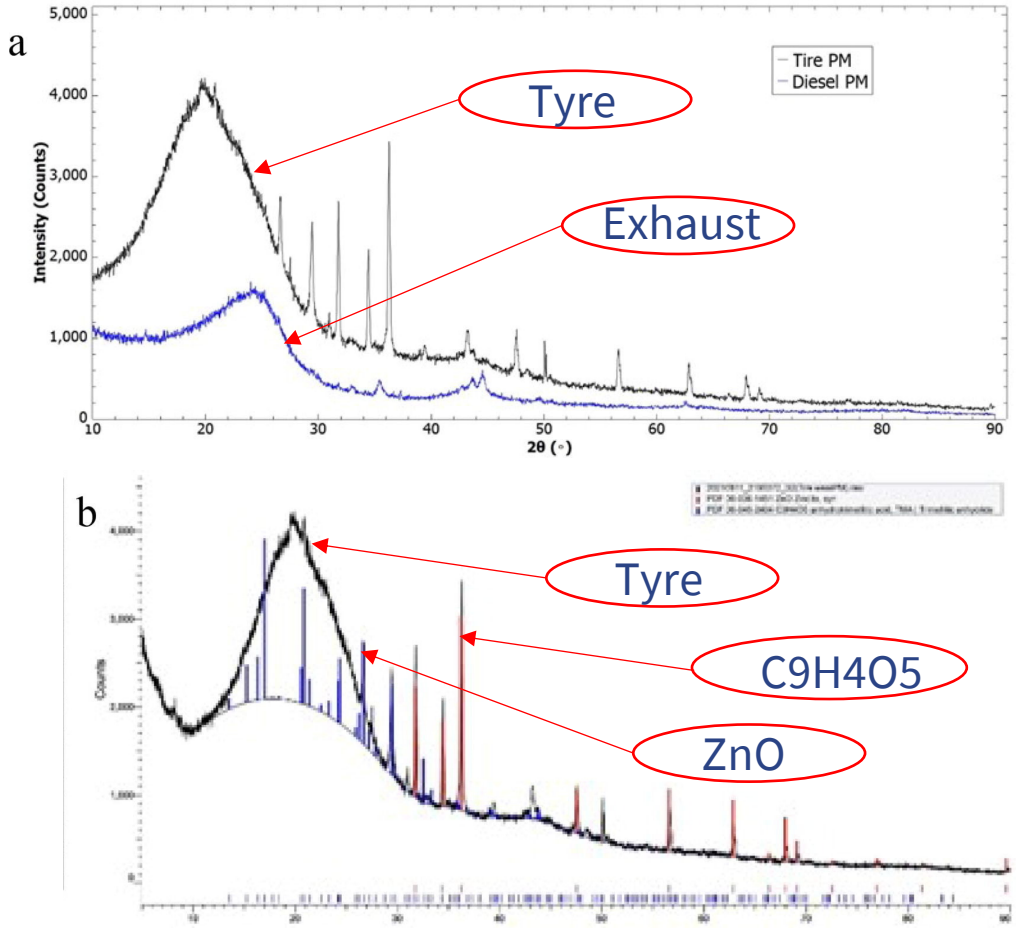


PM emissions from vehicular exhaust and non-exhaust sources in megacity Delhi

Zn is a marker or tracer for tyre wear PM in overall analysis of atmospheric PM

Euro 7 also aims to introduce additional measures for measuring tyre abrasion and checking particulate emissions from brake components.

For tyres, there is a possibility that even non-Euro 7 relevant vehicles will need to be fitted with Euro-7 compliant tyres.



Literature suggests C9H4O5 peaks can also represent end product of the oxidation of polycyclic aromatic hydrocarbons

Oh, Ban-seok, et al. "Characterization of biodiesels and tire derived particulate matters in morphology and nanostructure." Materials Today: Proceedings 66 (2022): 2756-2761.

CNR

engine exhaust catalyst

X-RAY BASED TECHNIQUES FOR TRANSPORTATION APPLICATIONS

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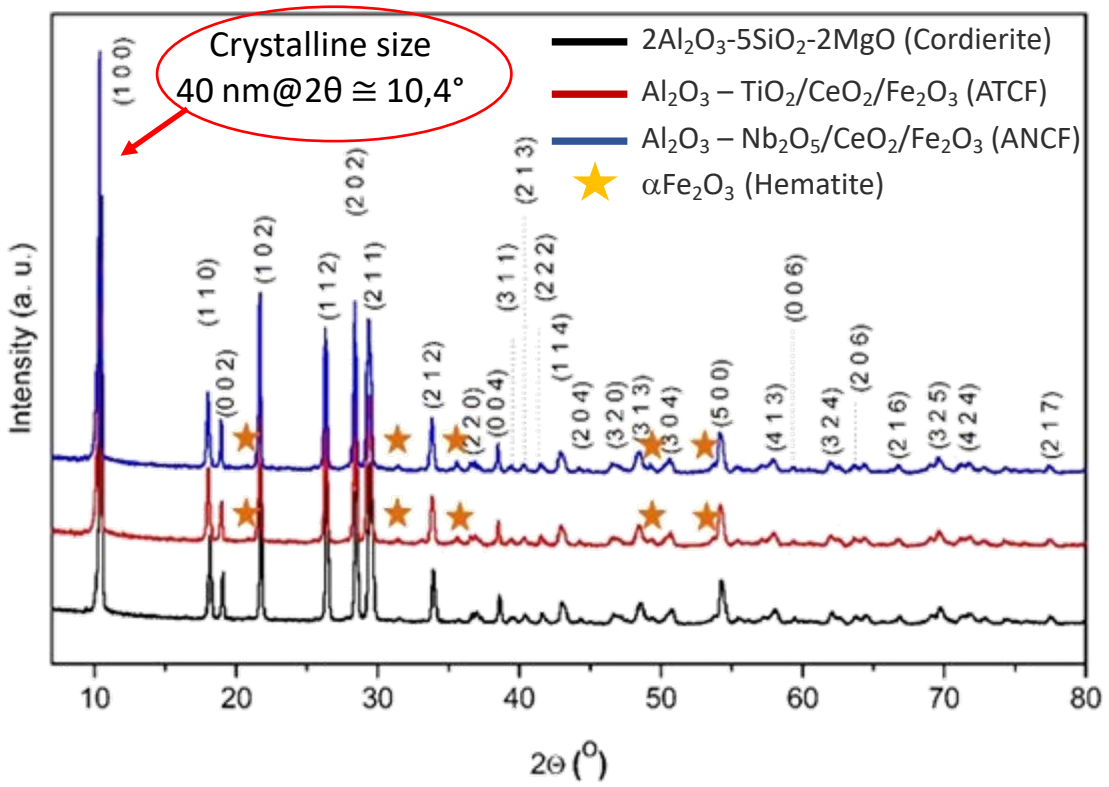
ENGINE EXHAUST CATALYST

X-ray Diffraction



Crystal structure influences the catalyst activity: i.e. in SCRs. the crystalline structure significantly enhances NO_2 formation, causing more rapid selective catalytic reduction (SCR) reactions and greater catalyst reducibility for NOX decomposition

X-ray Fluorescence

		Cordierite	ATCF	ANCF
Elements	NaO	0.146	0.163	0.160
	MgO	13.800	13.200	14.300
	Al_2O_3	34.100	32.900	33.900
	SiO_2	50.300	48.500	48.100
	P_2O_5	0.036	0.032	0.029
	SO_3	0.052	0.034	0.022
	K_2O	0.189	0.179	0.154
	CaO	0.321	0.217	0.201
	TiO_2	0.249	0.445	0.204
	Fe_2O_3	0.442	3.670	2.250
	Nb_2O_5	–	–	0.086
	CeO_2	–	0.045	0.174
	WO_3	0.312	0.585	0.429

Resitoglu, I. A., Altinisik, K., Keskin, A., & Ocakoglu, K. (2020). The effects of Fe2O3 based DOC and SCR catalyst on the exhaust emissions of diesel engines. Fuel, 262, 116501.

XRF allows estimating quality efficacy of Coating materials penetration into the cordierite monolith structure.

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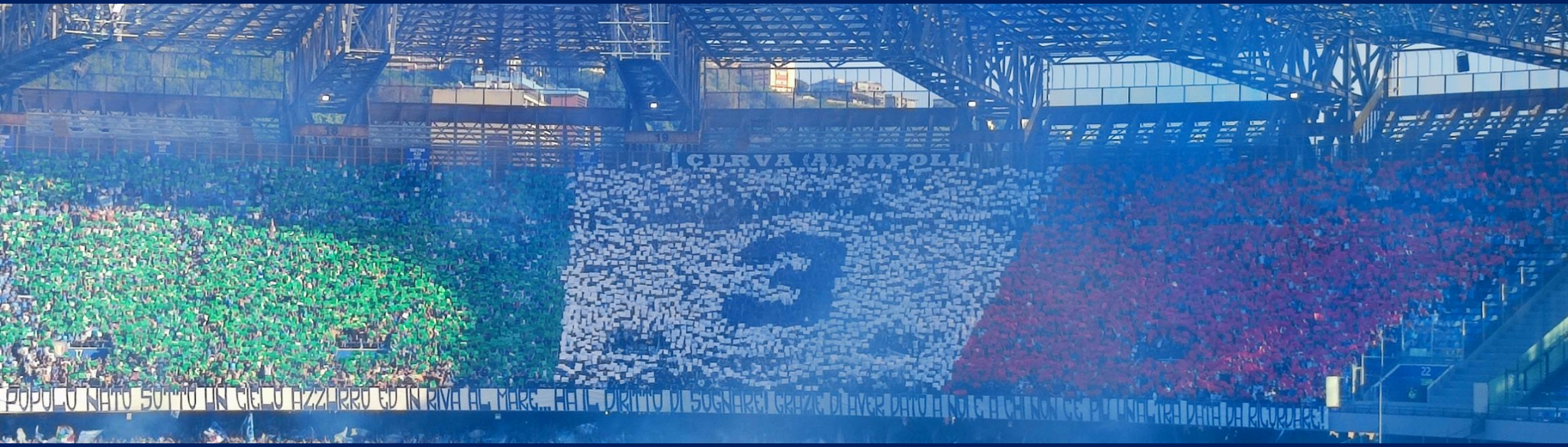

Thank You For Your Attention !

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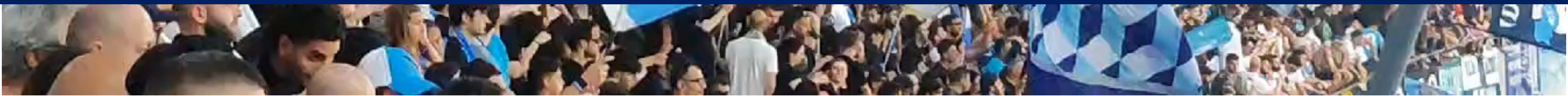

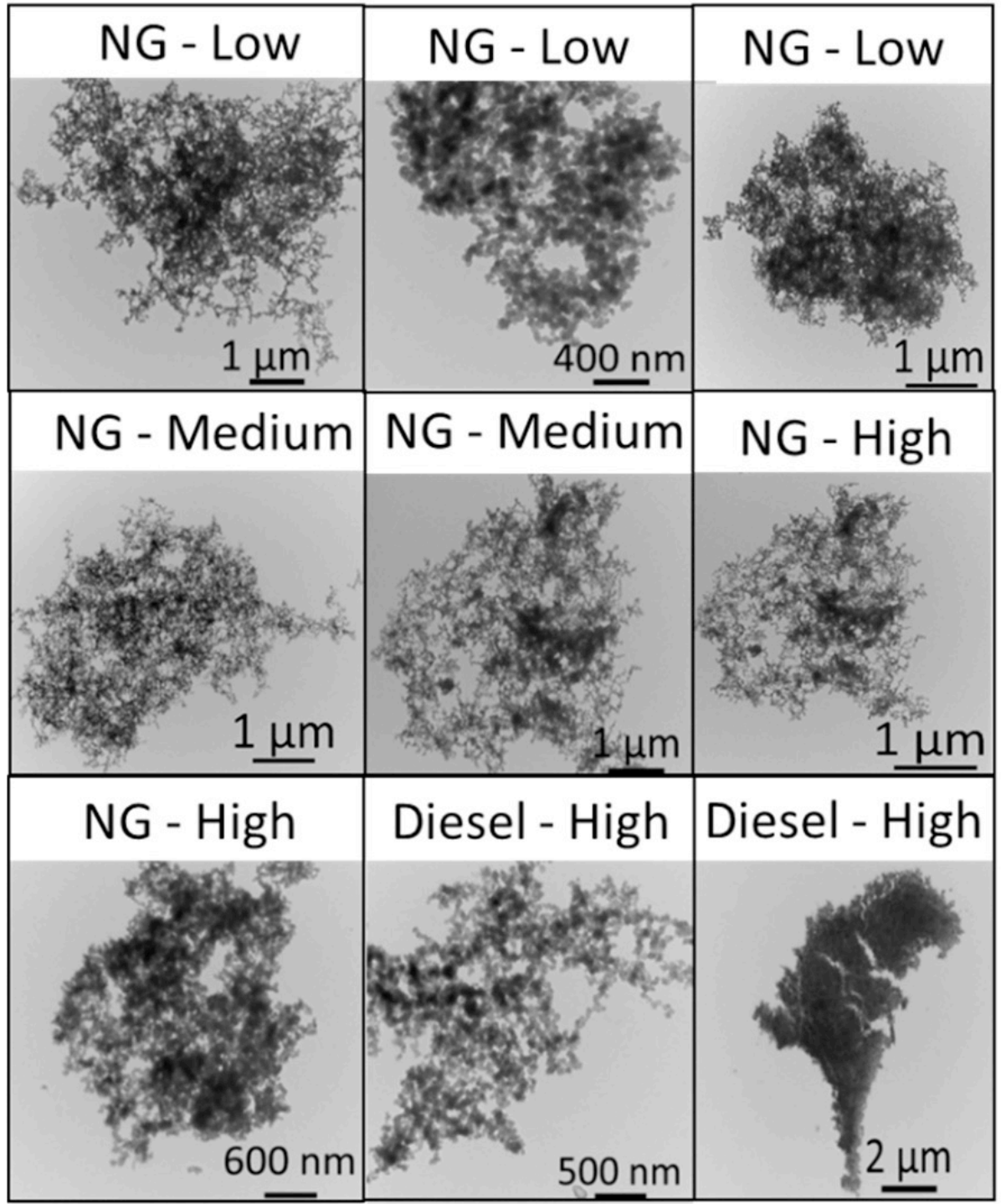
NG - Low
1 µm
NG - Low
400 nm
NG - Low
1 µm
NG - Medium
1 µm
NG - Medium
1 µm
NG - High
1 µm
NG - High
600 nm
Diesel - High
500 nm
Diesel - High
2 µm