2.61 Internal Combustion Engines
Spring 2008

Diesel Emissions and Control

- Diesel emissions
- Regulatory requirements
- Diesel emissions reduction
- Diesel exhaust gas after-treatment systems
- Clean diesel fuels

Diesel Emissions

- CO – not significant until smoke-limit is reached
    - Overall fuel lean
    - higher CR favors oxidation
- HC – not significant in terms of mass emission
    - Crevice gas mostly air
  - Significant effects:
    - Odor
    - Toxics (HC absorbed in fine PM)
  - Mechanisms:
    - Over-mixing, especially during light load
    - Sag volume effect
- NOx – very important
    - No attractive lean NOx exhaust treatment yet
- PM – very important
    - submicron particles health effects

Diesel HC emission mechanisms

Demonstration of over-mixing effect

Effect of nozzle sac vol. on HC emissions

NOx mechanisms

- NO: Extended Zeldovich mechanism

  $N_2 + O \leftrightarrow NO + N$

  $N + O_2 \leftrightarrow NO + O$

  $N + OH \leftrightarrow NO + H$

  - Very temperature sensitive: favored at high temperature
  - Diffusion flame: locally high temperature
  - More severe than SI case because of higher CR
- NO_2 : high temperature equilibrium favors NO, but NO2 is formed due to quenching of the formation of NO by mixing with the excess air

  $NO + HO_2 \leftrightarrow NO_2 + OH$

  $NO_2 + O \leftrightarrow NO + O_2$

  - Gets 10-20% of NO_2 in NO_x

NOx formation in Diesel engines

Normalized NO concentration from cylinder dumping experiment. Injection at 27º BTC. Note most of the NO is formed in the diffusion phase of burning

NOx and NO emissions as a function of overall equivalence ratio Φ. Note that NO_2 as a fraction of the NOx decreases with increase of Φ.

Diesel combustion

Image removed due to copyright restrictions. Please see: Flynn, Patrick F., et al. "Diesel Combustion: An Integrated View Combining Laser Diagnostics, Chemical Knetics, and Empirical Validation." *SAE Journal of Engines* 108 (March 1991): SP-1444.

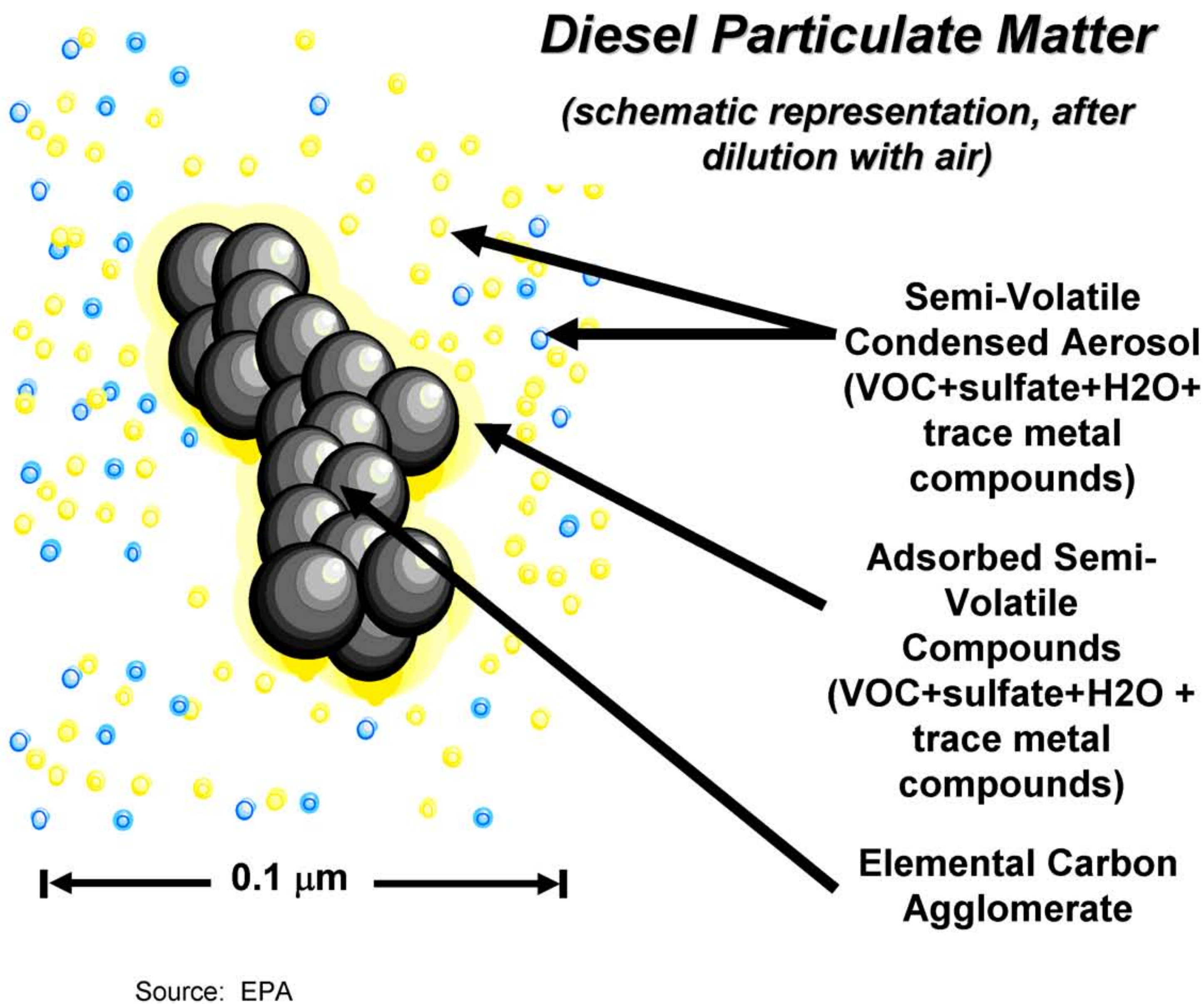
Particulate Matter (PM)

- As exhaust emission:
  - visible smoke
  - collector of organic and inorganic materials from engine
    - Partially oxidized fuel; e.g. Polycyclic Aromatic Hydrocarbons (PAH)
    - Lubrication oil (has Zn, P, Cu etc. in it)
  - Sulfates (fuel sulfur oxidized to SO2, and then in atmosphere to SO3 which hydrates to sulfuric acid (acid rain)

Particulate Matter

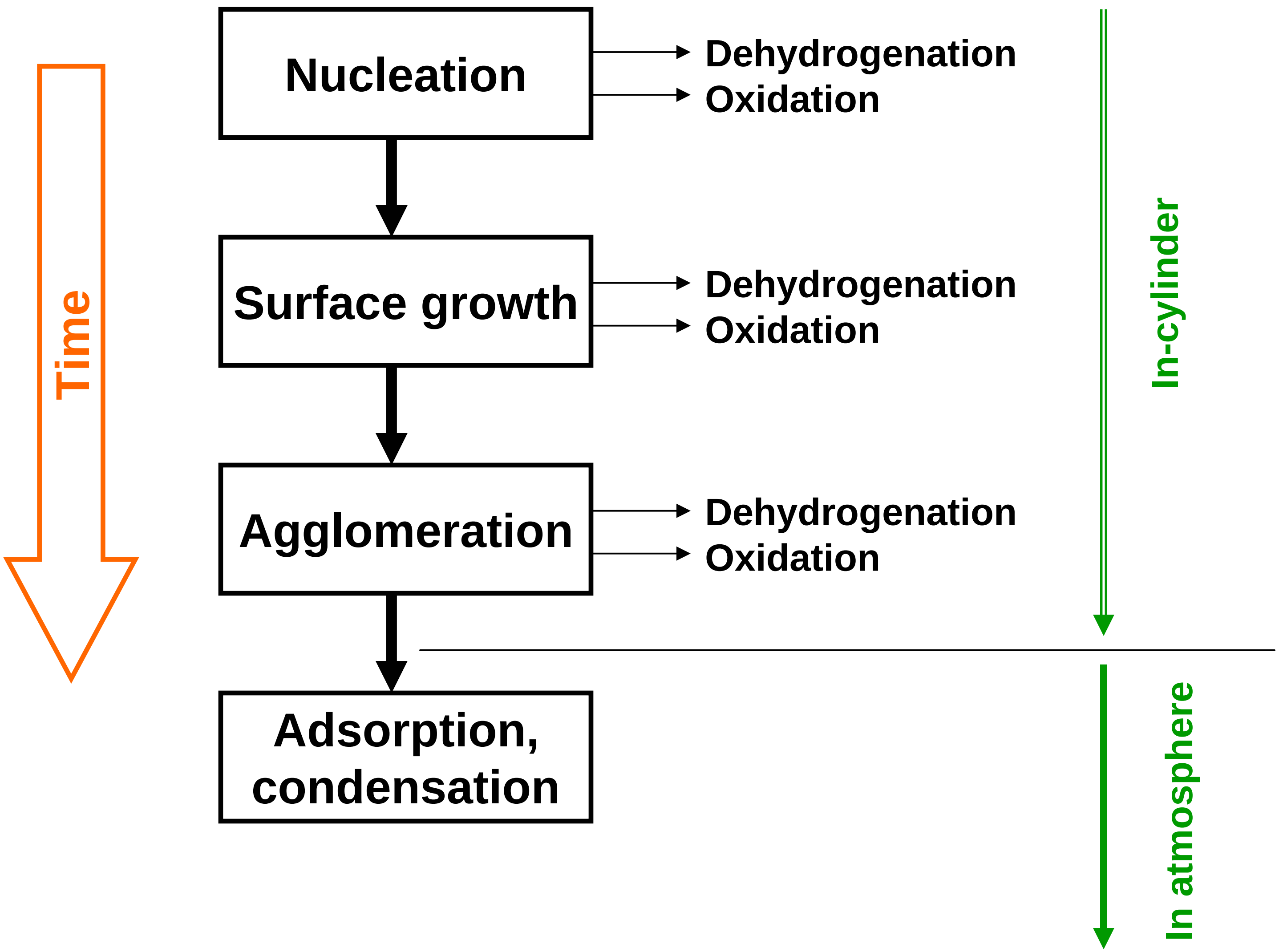
- In the combustion process, PM formed initially as soot (mostly carbon)
  - partially oxidized fuel and lub oil condense on the particulates in the expansion, exhaust processes and outside the engine
    - PM has effective absorption surface area of 200 m^2/g
  - Soluble Organic Fraction (SOF) 10-30%
    - (use dichloromethane as solvent)

Elementary soot particle structure

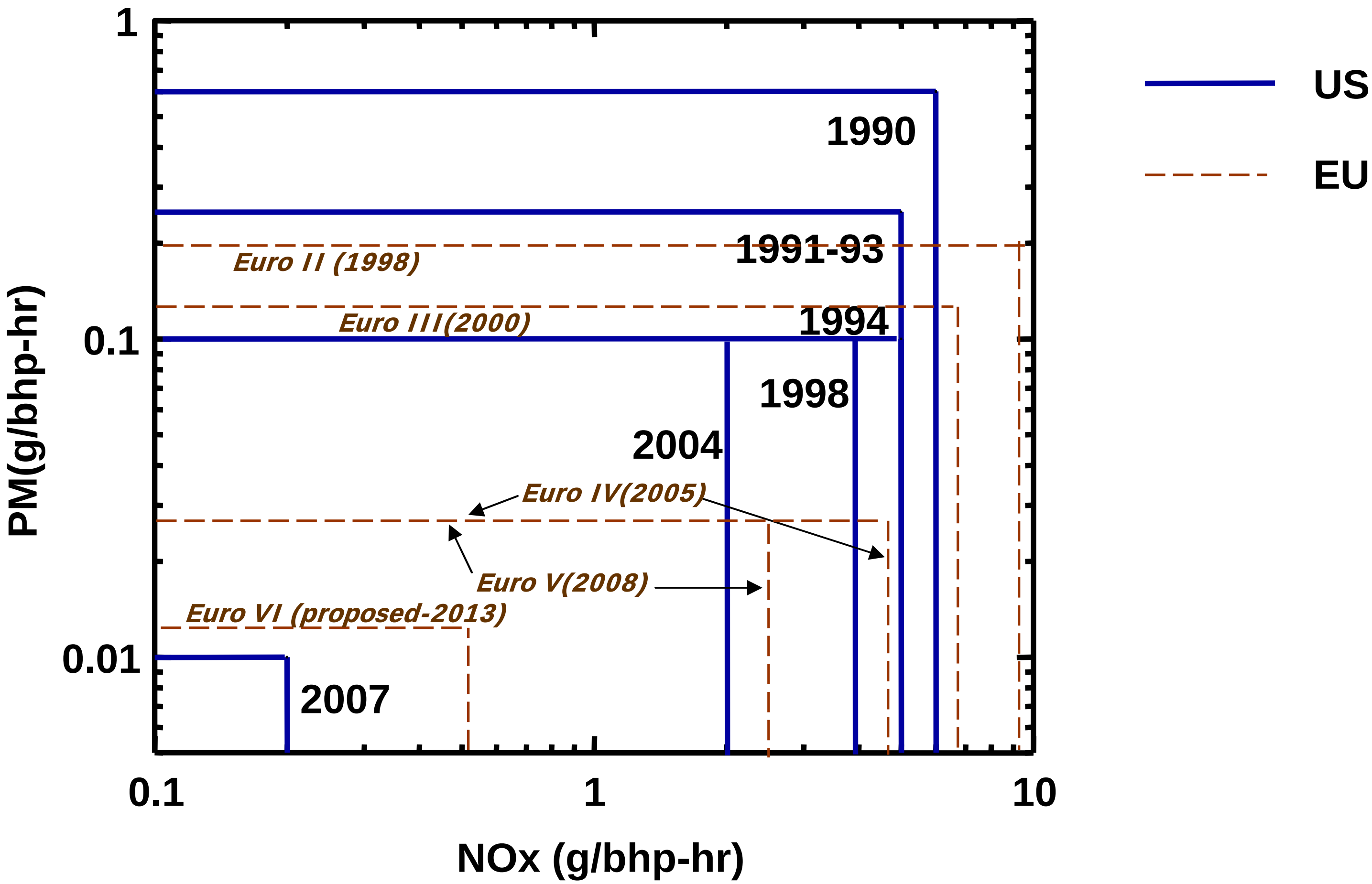


Source: Environmental Protection Agency, www.epa.gov.

PM formation processes



Diesel NOx/PM regulation



(Note: Other countries regulations are originally in terms of g/KW-hr)

Diesel Emissions Reduction

1. Fuel injection: higher injection pressure; multiple pulses per cycle, injection rate shaping; improved injection timing control
2. Combustion chamber geometry and air motion optimization well matched to fuel injection system
3. Exhaust Gas Recycle (EGR) for NOx control
   - Cooled for impact
4. Reduced oil consumption to reduce HC contribution to particulates
5. Exhaust treatment technology: NOx, PM
6. Cleaner fuels

Effect of EGR

1.35 L single cylinder engine, Direct Injection, 4-stroke

Split Injection

PM Control

Images removed due to copyright restrictions. Please see: Zelenka, P., et al. "Ways Toward the Clean Heavy-duty Diesel." *SAE Journal of Engines* 99 (February 1990): 900602.

Post injection filter regeneration

- **Regeneration needs ~550^{o}C**
- **Normal diesel exhaust under city driving ~150-200^{o}C**
- **Need oxidation catalyst (CeO_2) to lower light off temperature**
- **Control engine torque**
- **Minimized fuel penalty**

Peugeot SAE 2000-01-0473

Increase exhaust gas temperature by injection of additional fuel pulse late in cycle.

Diesel particulate filters use porous ceramics and catalyst to collect and burn the soot

Please see slide 9 in Johnson, Tim. "Diesel Exhaust Emission Control." Environmental Monitoring, Evaluation, and Protection in New York: Linking Science and Policy, 2003.

State-of-the Art SCR system has NO2 generation and oxidation catalyst to eliminate ammonia slip

Image removed due to copyright restrictions. Please see p. 9 in "Recent Developments in Integrated Exhaust Emission Control Technologies Including Retrofit of Off-Road Diesel Vehicles." Manufacturers of Emissions Controls Association, February 3, 2000.

Integrated DPF and NOx trap

Image removed due to copyright restrictions. Please see: Fig. 3 in Nakatani, Koichiro, et al. "Simultaneous PM and NOx Reduction System for Diesel Engines." *SAE Journal of Fuels and Lubricants* 111 (March 2002): SP-1674.

From Toyota SAE Paper 2002-01-0957

Clean Diesel Fuels

1. Lower sulfur levels
   - 350 ppm $\rightarrow$ 15 ppm
2. Lower percentage aromatics
3. Oxygenated fuels
4. Higher cetane number
5. Narrower distillation range

Diesel Emission Control

Summary

- Emission regulations present substantial challenge to Diesel engine system
- Issues are:
  - performance and sfc penalty
  - cost
  - reliability
  - infra-structure support