# *Effects of Ambient Density and Temperature on Soot Formation under High-EGR Conditions*

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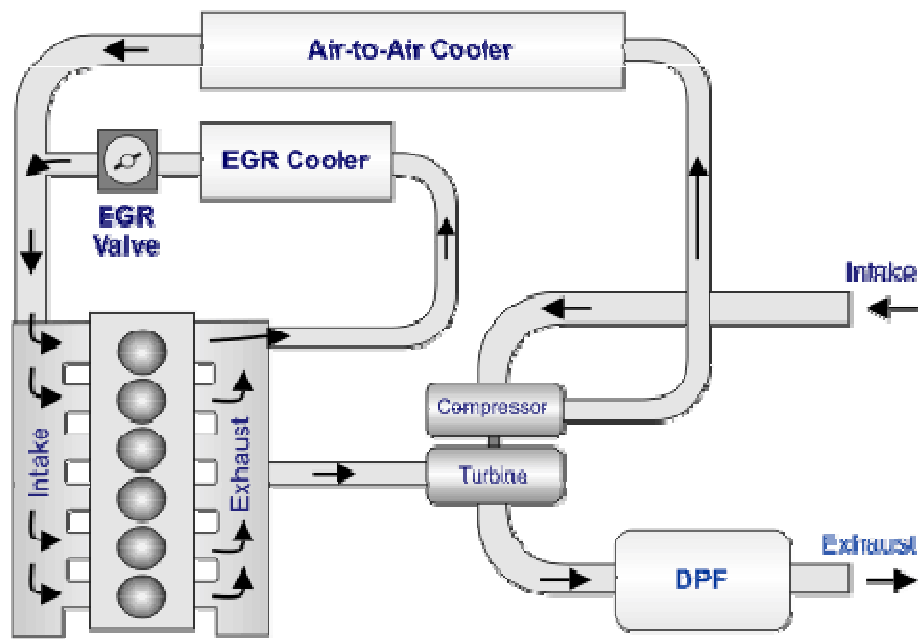
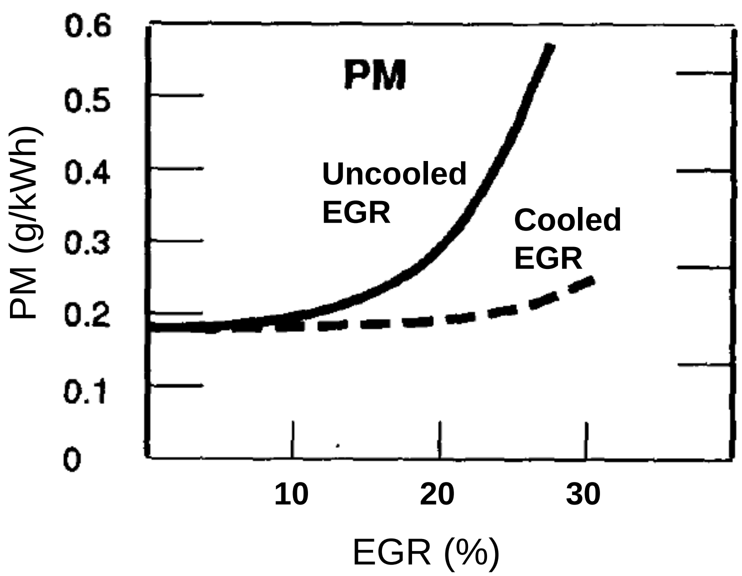
# *Likely consequences of using heavy EGR, especially at high load*

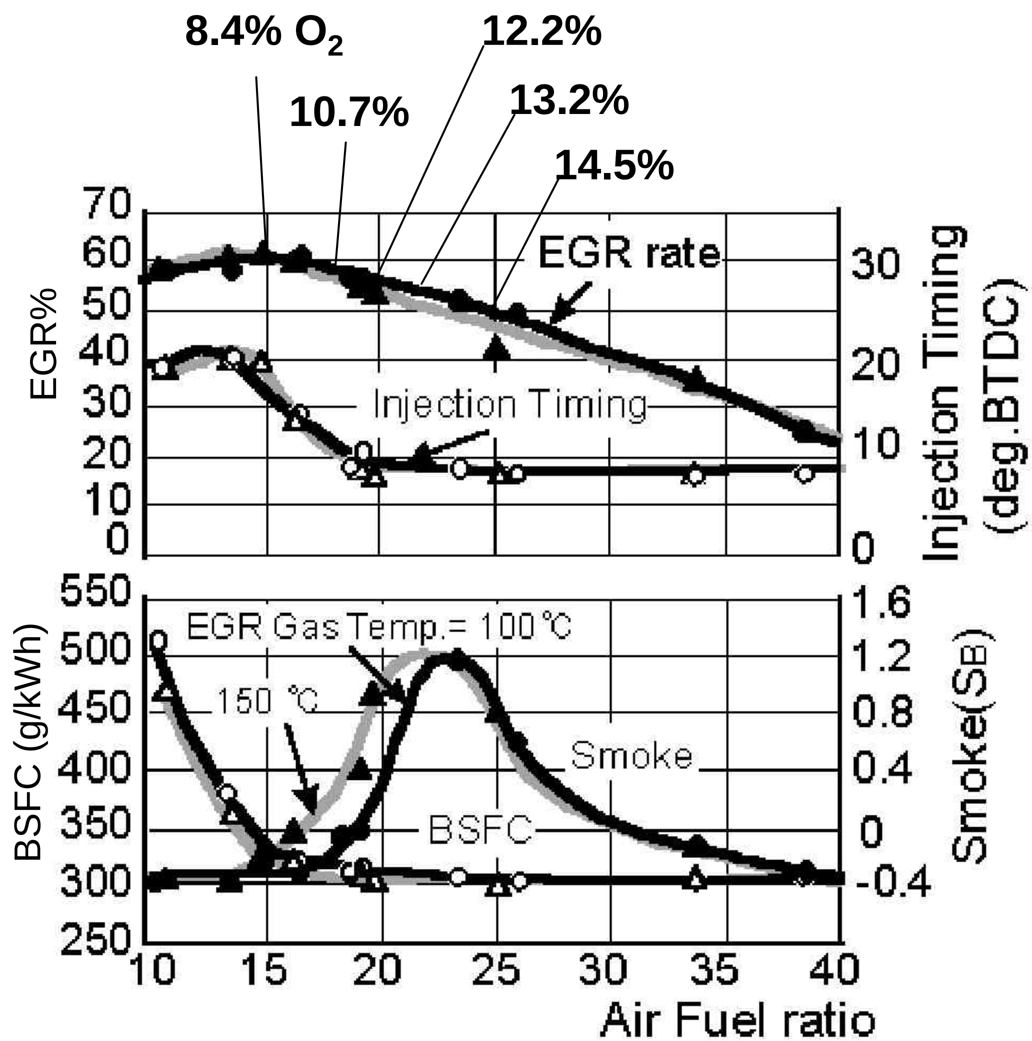
- **EGR temperature rises**
  - **Can't cool all of the EGR**
  - **Intake and TDC charge-gas (ambient) temperature increases.**
  - **Shortens ignition delay (prevents low $\phi$ combustion)**
  - **Temperature also inherently affects soot processes (formation and oxidation)**
- **Intake pressure (boost) increases**
  - **EGR reduces intake oxygen mole fraction**
  - **Compensate by using boost to deliver needed oxygen**



# Cooled EGR reduces engine-out PM




Herzog et. al, 1992

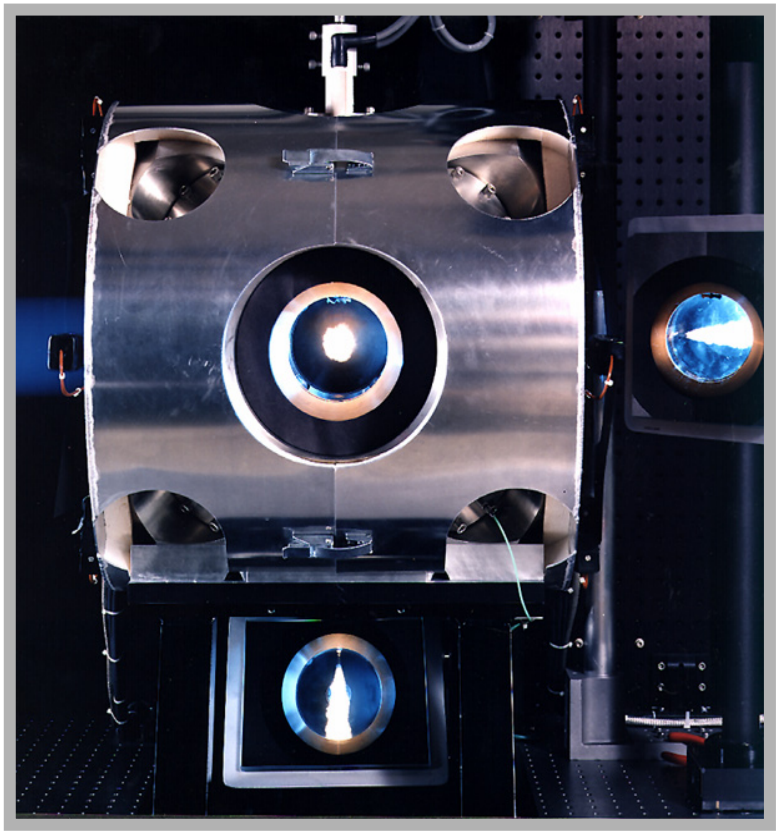


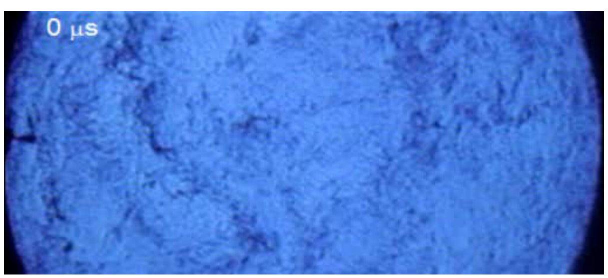

Akihama et. al, 2001

# *Objectives*

- **Measure soot formation with:**
  - **high-temperature / high-EGR combinations.**
  - **high-boost / high-EGR combinations.**
- **Distinguish between *in-situ* phenomena in reacting spray compared to engine-out PM.**
- **Focus on low-temperature regimes for soot formation.**
  - **Combustion where flame temperatures are low enough for manageable $NO_x$ formation (<15% $O_2$).**

# *Soot experiments in optically-accessible combustion vessel*



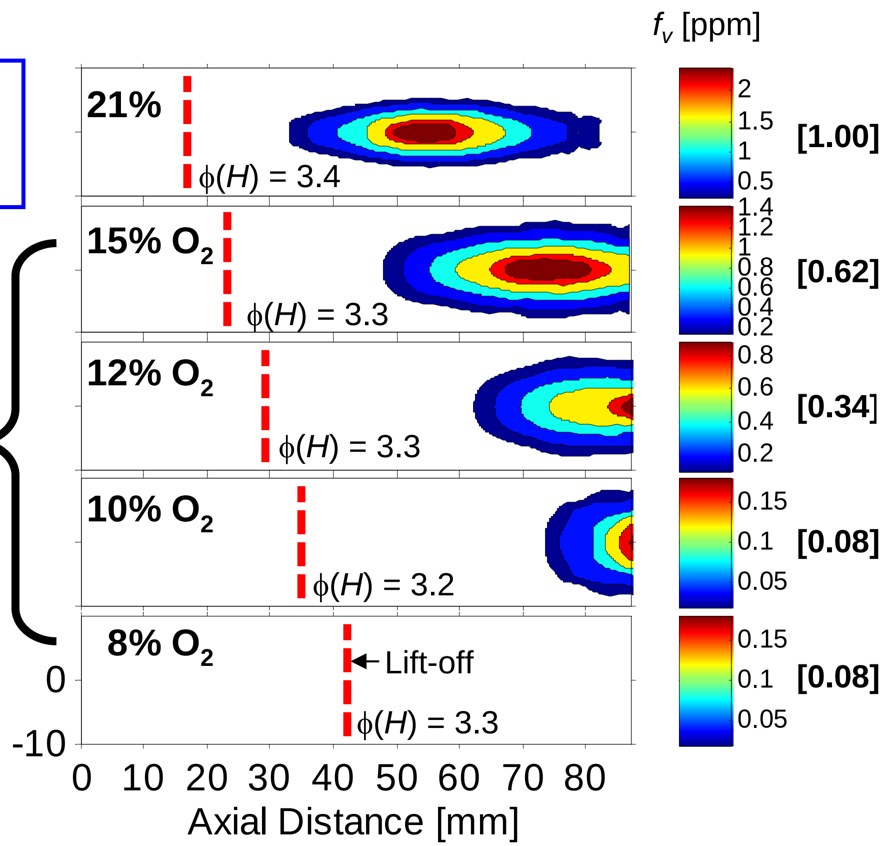



- **Ambient conditions:**
  - **8-21% $O_2$ (EGR).**
- **Injector**
  - **n-heptane**
  - **d = 100 μm**
- **Soot measurement**
  - **Laser extinction (quantitative)**
  - **PLII**
- **Chemiluminescence for lift-off length.**

# *Soot volume fraction decreases with increasing EGR*

$T_a$ = 1000 K,
$\rho_a$ = 14.8 kg/$m^3$

High-EGR
(Low NOx)




Decreasing $f_v$

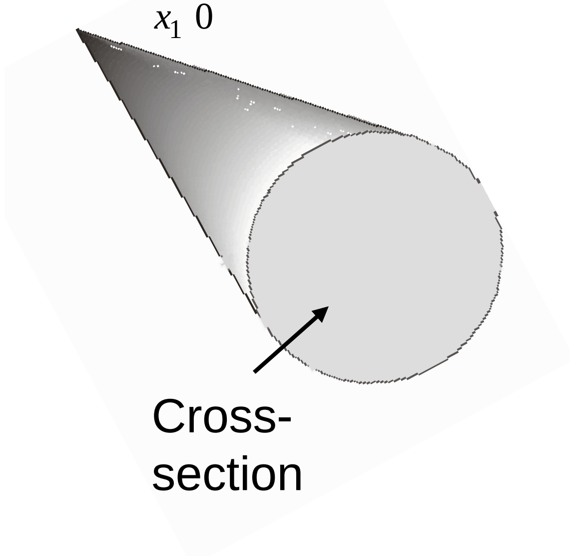
No Soot

- **Unique dataset available on the web for model development at LTC conditions.**
  - **Engine Combustion Network**
  - **http://www.ca.sandia.gov/ECN/**

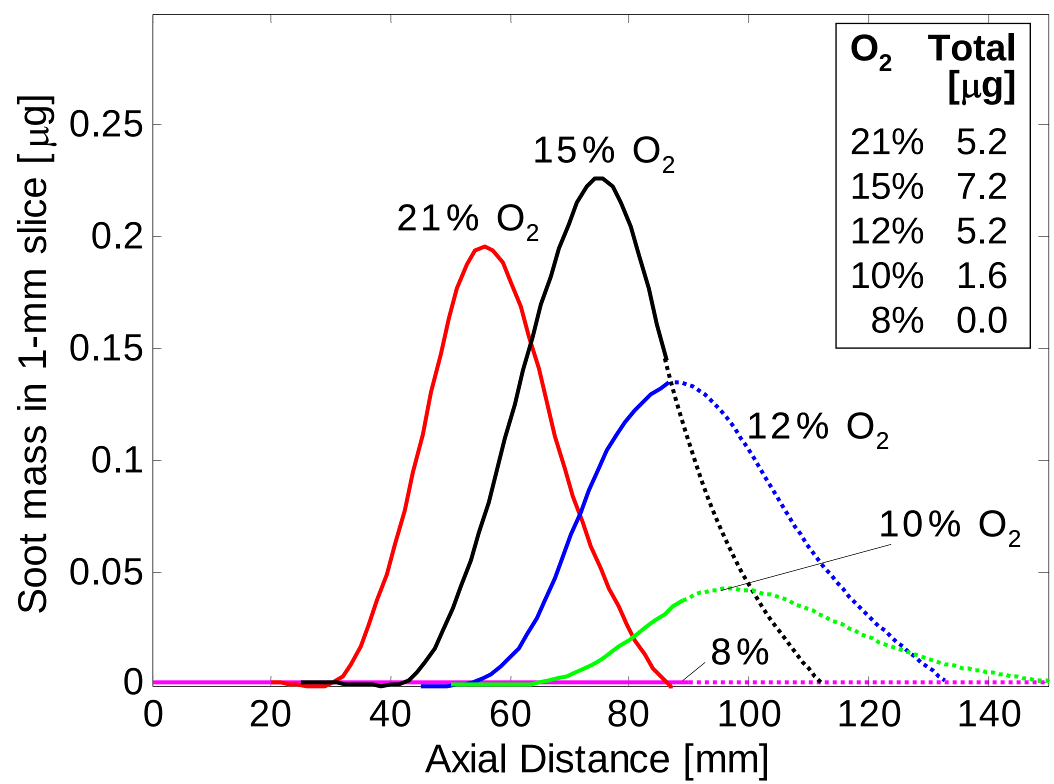
# Soot mass increases, then decreases with increasing EGR

**Soot mass Integral**

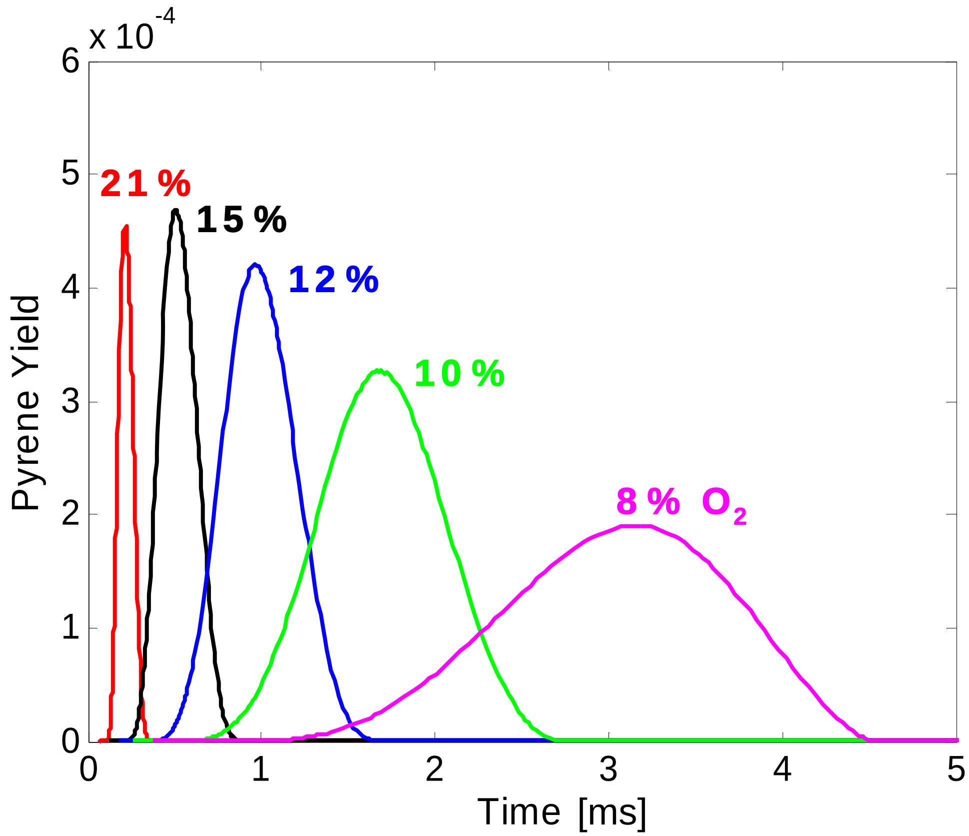
$$\rho_s \int_{x_1}^{x_2} \int_0^R f_v(r) 2\pi r \, dr \, dx$$




**$T_a$ = 1000 K, $\rho_a$ = 14.8 kg / m³**

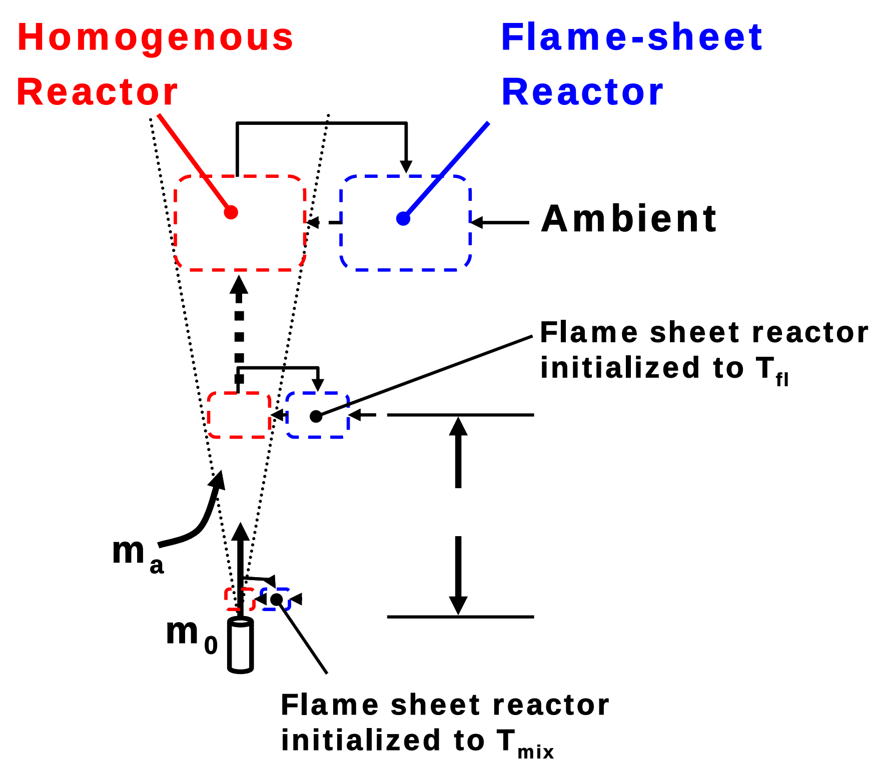


# *Rate of soot formation significantly decreases by using EGR.*




**TSL Model**

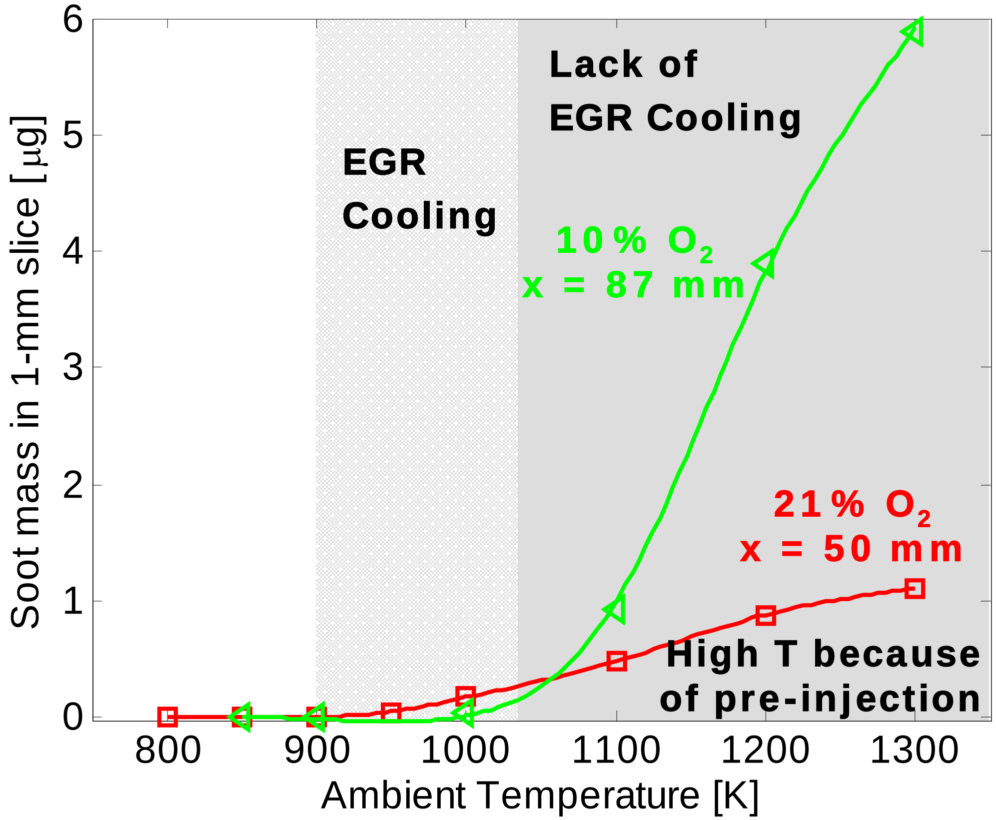
**(Broadwelland Lutz, 1998)**



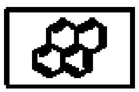

- **With decreasing ambient $O_2$:**
  - **Rate of formation decreases.**
  - **Time of first soot precursor formation increases.**
  - **BUT residence time for soot formation increases.**

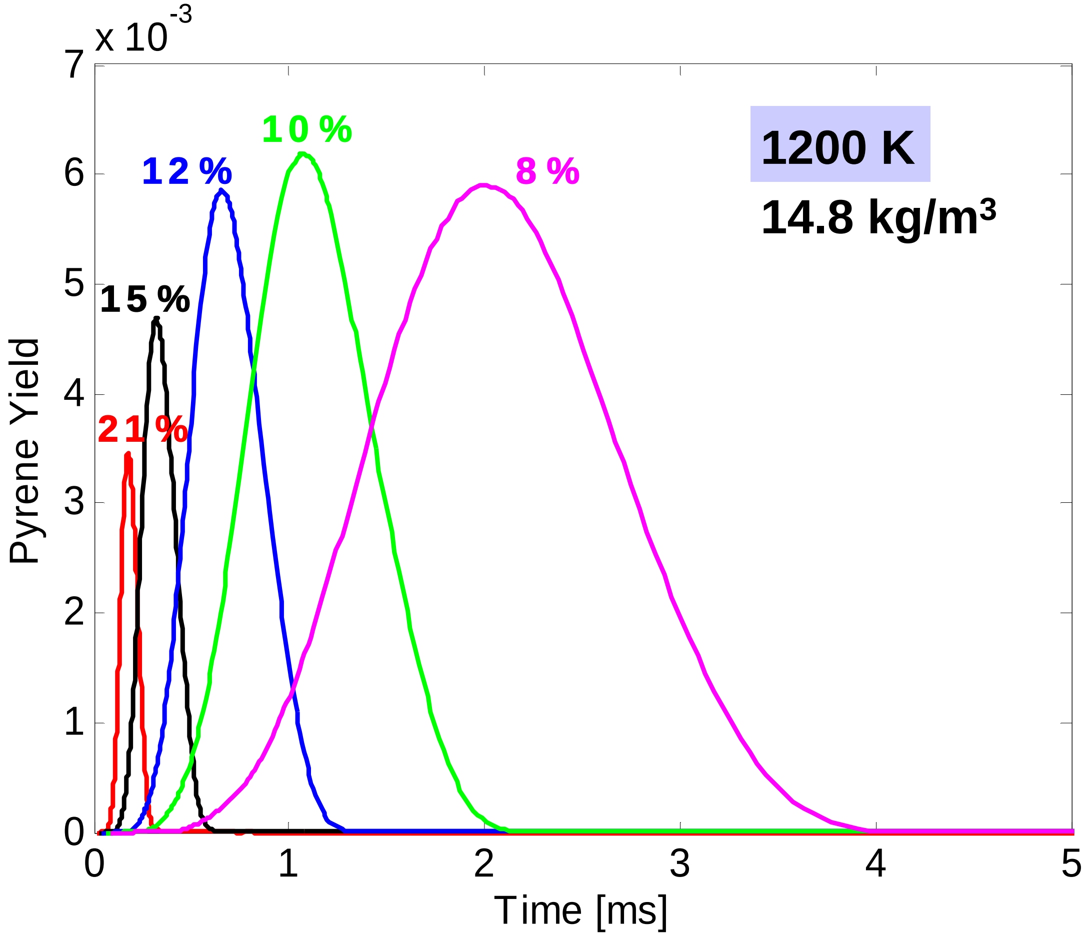
# *Soot increases rapidly for high-T, high-EGR conditions.*

**n-heptane, d = 100 μm, ρ = 14.8 kg/m³, $\Delta P_{inj}$ = 1500 bar**

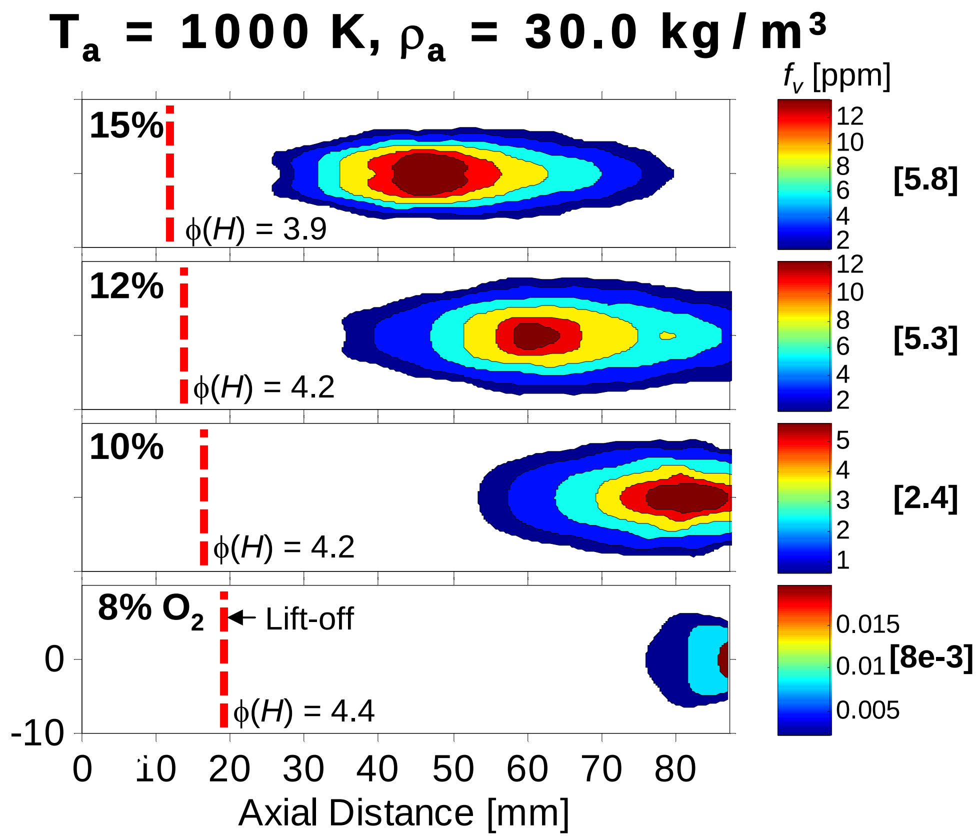


## *High EGR and $T_a$ provides longer residence time along with high soot formation rates.*



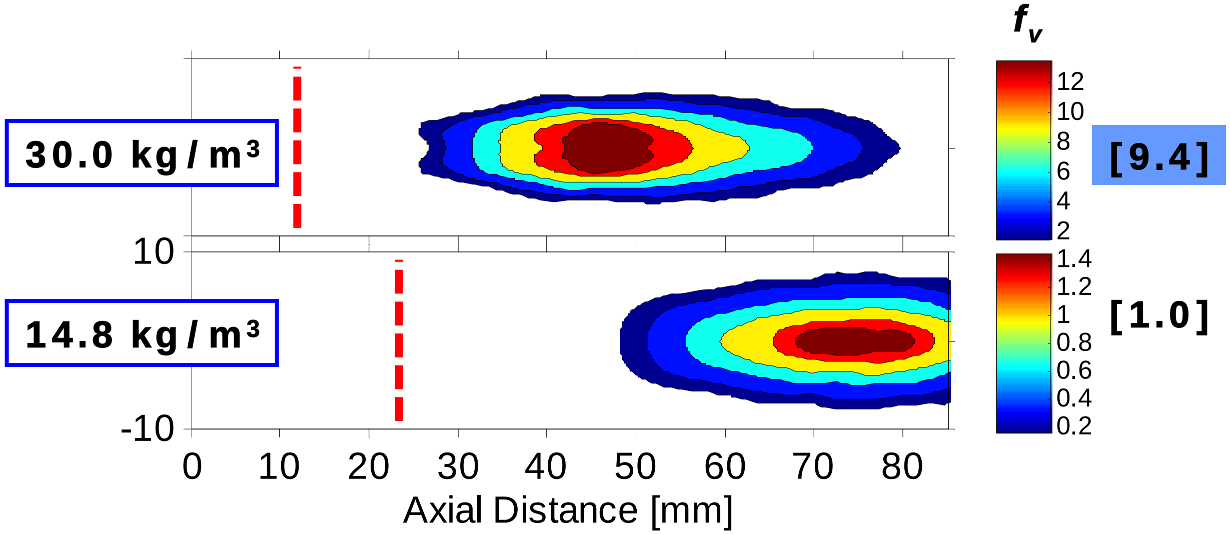


# Soot volume fraction increases with increasing ambient density.



# *Direct comparison shows soot strongly increases with increasing $\rho_a$.*

**$T_a$ = 1000 K,**
**15% $O_2$**



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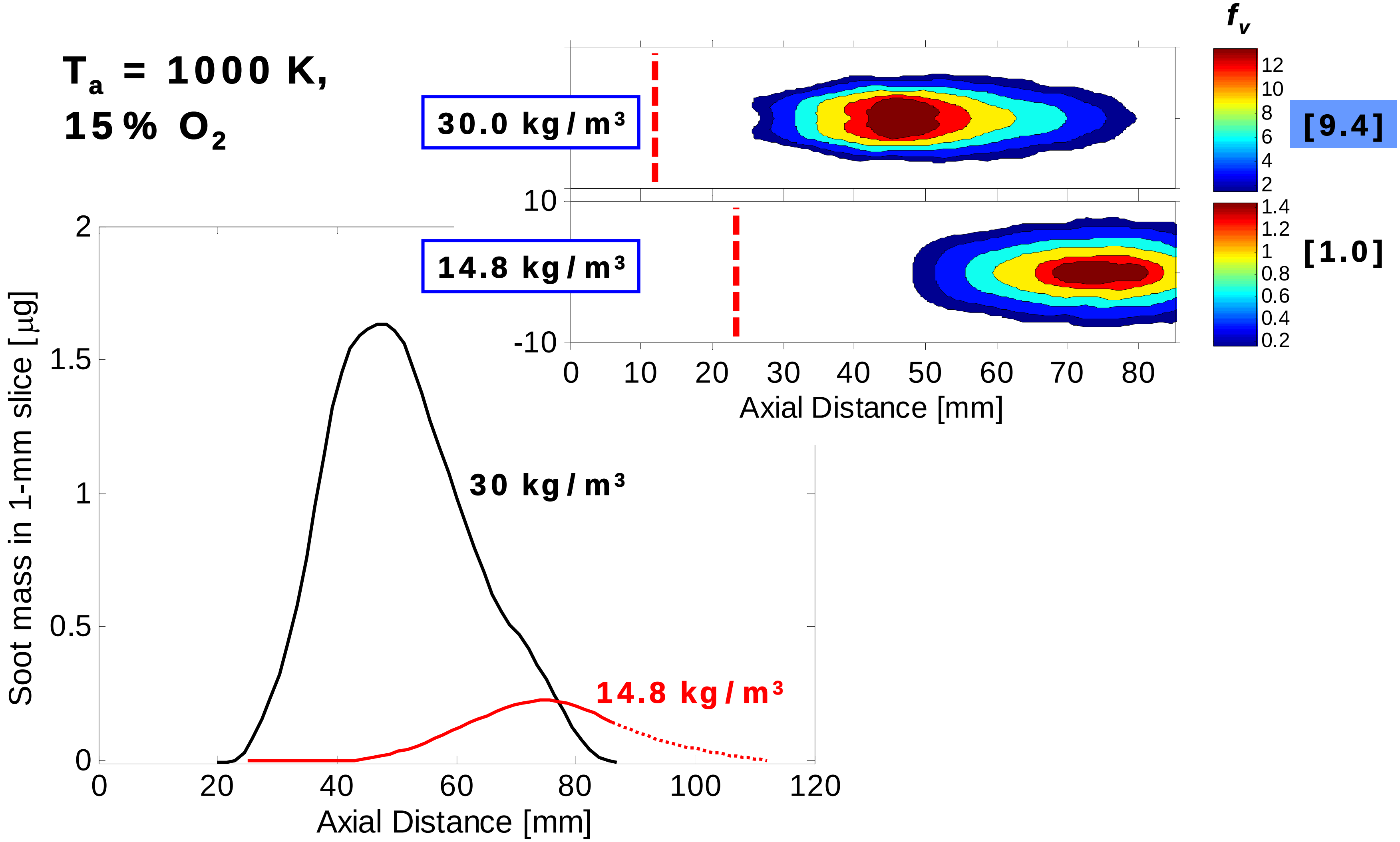
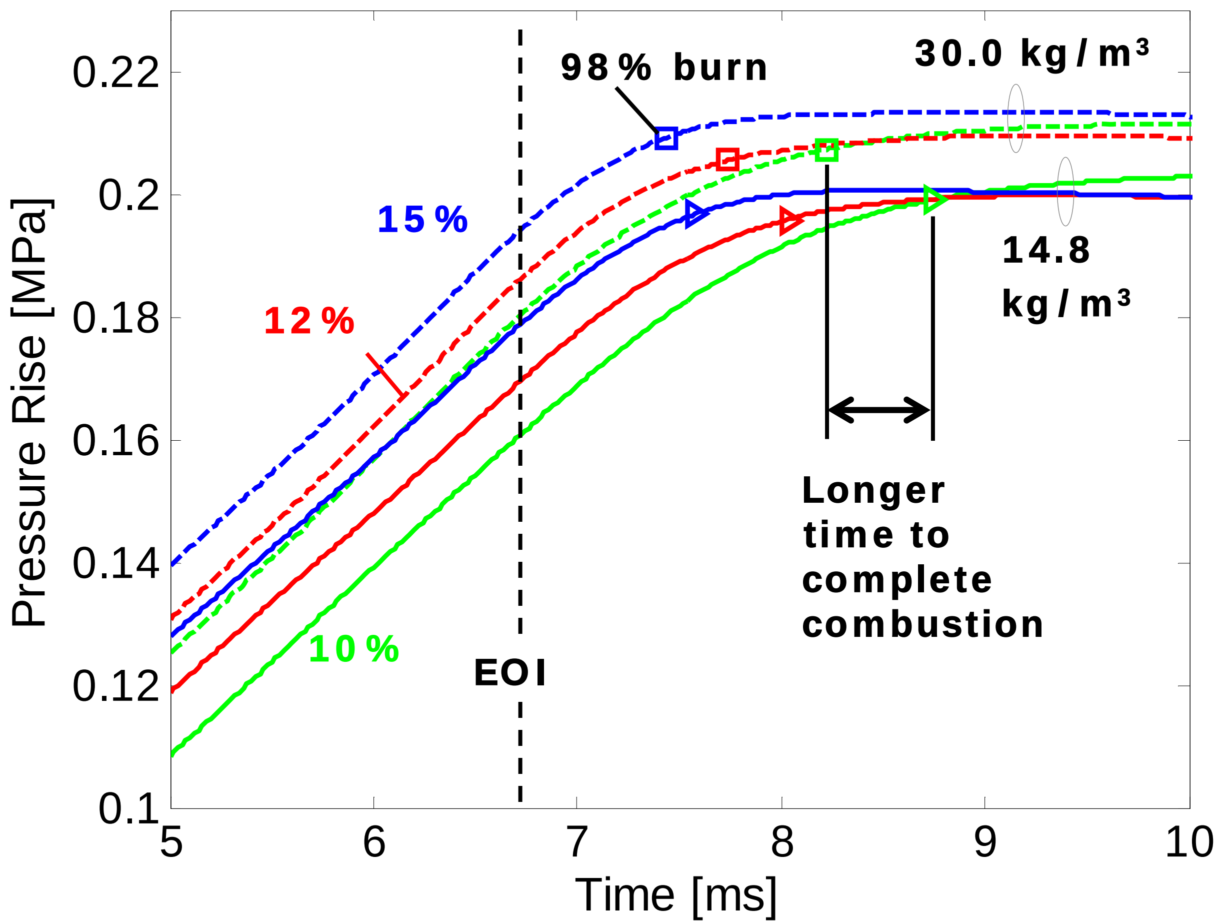
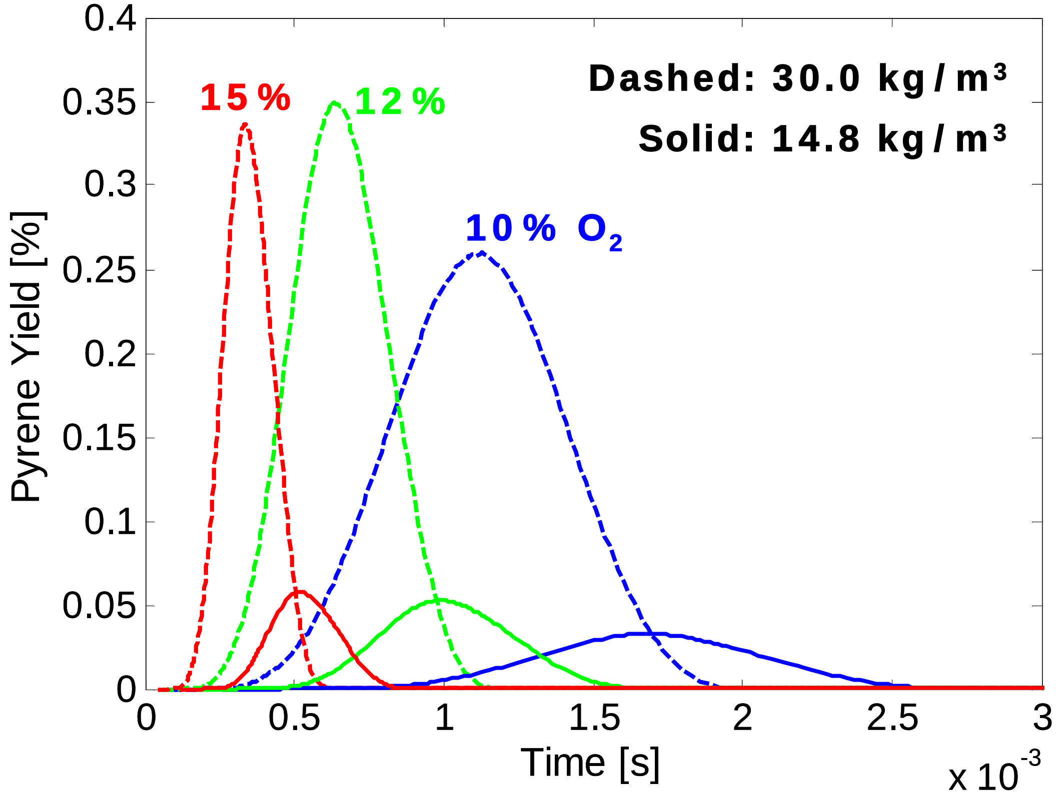


# *Mixing rate increases with increasing ambient density.*




- **With increasing density:**
  - **Time from EOI to EOC decreases.**
  - **Higher heat-release rate.**

# *TSL predictions show soot precursor formation rate increases with $\rho_a$.*



# Summary and Conclusions

- **High-EGR/high-ambient temperature combinations are highly sooting.**
  - **Importance of EGR cooling**
  - **May necessitate low CR/late injection**
  - **Avoiding interaction with pre-burn products**
- **High-boost (high ambient density) also causes increased soot <u>formation</u> at high-EGR conditions.**
  - **Total soot increases by more than a factor of five from 14.8 to 30 kg/$m^3$.**
  - **Soot increase would likely be worse, if not for the higher mixing rate.**
  - **Increase in soot formation offset by higher mixing rate, higher soot oxidation.**