Particle Formation in Aircraft Engines

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Aftertreatment systems can not be used in aircraft gas turbines. Therefore emission reduction is only possible by improving the combustion systems. In actual gas turbines, the fuel is injected as fuel droplets into the combustor. A diffusion flame is stabilized in the combustor. In order to keep combustor exit temperatures “low”, the overall equivalence ratio inside the combustor is very lean. But the local equivalence ratio around the fuel droplets is very rich. Far away from the droplets it’s very lean. Soot is formed in the local rich flame zones.

Measurements show very high soot concentrations inside aircraft gas turbine combustors. The soot concentration can be at least two or three orders of magnitude higher than at combustor exit. The high soot concentrations inside the combustor can not be explained by HACA soot formation mechanism (Hydrogen Abstraction Carbon Addition). Therefore a new “Direct Soot Formation Mechanism” is suggested.

Jet fuel contains aliphatic molecules from C8 to C16. In a gas turbine combustor, the fuel spray is injected into hot compressed air. Fuel molecules vaporize from the spray droplets and heat up by heat transfer and flame radiation, before reaching the flame zone. Some fuel molecules crack by pyrolysis and built radicals and ions. These radicals and ions can recombine and built first clusters. If this happens, soot formation can start before the fuel molecules reach the flame region!

But the main part of soot formation takes place inside the flame zone, in fuel rich regions. Fuel molecules are cracked by pyrolysis and oxidation. This results in high concentrations of fuel-radicals and fuel-ions. The recombination of this radicals and ions built first clusters (macromolecules). These first clusters have very low density. The formation of the first soot particles in the flame results from further cluster growth, cluster agglomeration and cluster densification. The densification is a result of the formation of more and more C=C double bonds (sp^2) and the formation of new C-C bonds inside the cluster. The aliphatic side branches of the particles are burned preferably. At the end, the density and the C/H ratio of the soot particles is a function of residence time, temperature history and phi history of the individual particles. Densification and graphitization takes place on the way through the combustor. At combustor exit we see the well known soot particles.

In the direct soot formation mechanism, it is not necessary to crack the fuel molecules down to acetylene, to built the first aromatic rings. Aromatic rings can be formed directly via aliphatic rings. “Direct Soot” is a complex, low density, three dimensional polymer of fuel molecules. During the way through the combustor, “direct soot” is transformed to soot particles.
With the “Direct Soot Mechanism”, it is easy to explain fast soot formation from fuel molecules to soot particles.

Soot formation is a mixing problem! The next generation of aircraft gas turbines will have “Lean, Premixed, Prevaporized” combustors (LPP). There will be no fuel rich zones in the flame. Therefore there will be no soot formation and no soot emission!
In the near future, soot will only be a ground transportation problem.

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modern gas turbines show no visible soot, even at "Take Off". No aftertreatment possible!

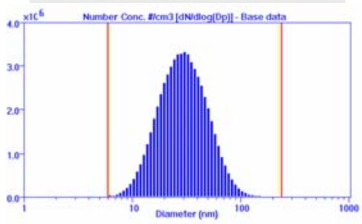
Soot is a Mixing Problem !

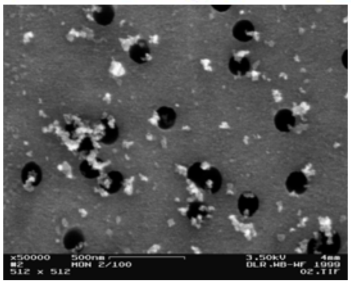
- liquid fuel is injected as droplet into the combustor
- only the evaporated and air mixed fuel can be ignited
- **soot is formed in local fuel rich flame zones around the droplets**
- particles move on the **"coldest trajectory"** through the combustor
- in the flame there is: soot formation and surface growth
  soot oxidation
  soot agglomeration
  soot densification
  pollutant formation
  and fuel oxidation all in parallel

EI's for existing Engines:

NOx	1 – 9 g/kg$_{fuel}$
CO	1 – 67 g/kg$_{fuel}$
Soot	10 – 400 mg/kg$_{fuel}$ # ~ E16 / kg$_{fuel}$
UHC	0 - 30 g/kg$_{fuel}$
Aldehyde	0 - 6,2 g/kg$_{fuel}$

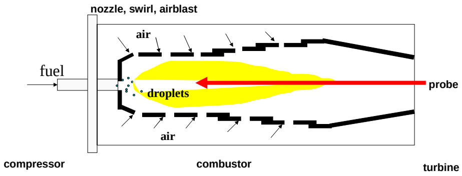
Typical size distribution of actual flight gas turbine



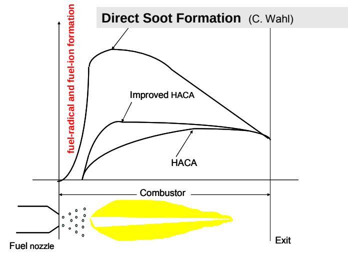


all SEM pictures are done by
Roland Borath, DLR, WB-WF

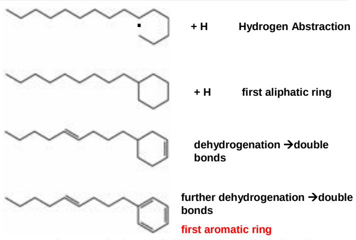
Combustor tubular or annular



diffusion flame with local fuel rich flame zones

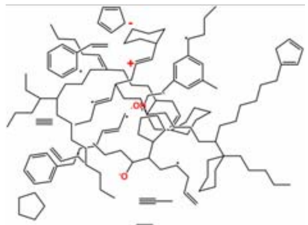


Formation of first aromatic ring



no need to crack the fuel down to small molecules (acetylene) !!

Formation of first cluster



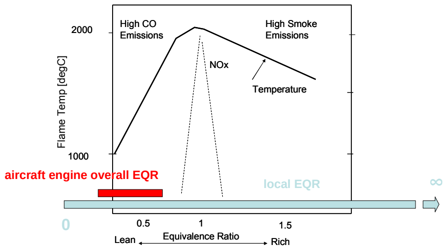
In addition to existing HACA mechanism

Soot is formed by:

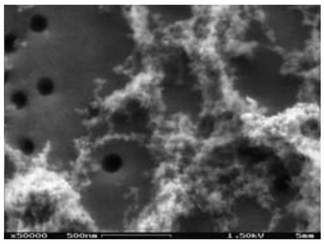
Direct Soot Formation

- First Cluster formation and growth, without cracking fuel molecules down to C2 or C3 → clusters with very low density
- Cluster densification, dehydrogenation → more and more double bonds and aromatic rings
- cluster agglomeration
- Oxidation of side branches → particles are more and more spherical
- First Clusters can not be measured by LII, because of gas and UHC inside. Clusters will "explode" when heated by LII beam!
- LII works only with black carbon

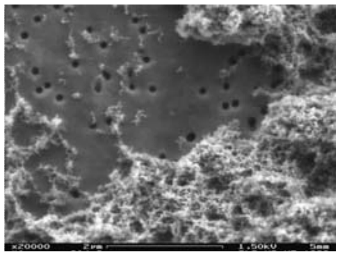
Pollutant formation vs. EQR

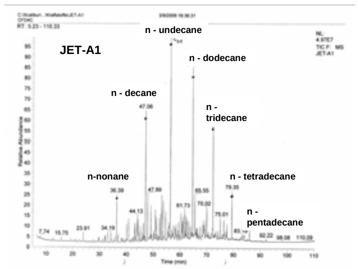


Soot concentration inside the combustor can be more than 1000 times higher than at the combustor exit



Due to the measured high soot concentrations inside the combustor, there must be another fast soot formation mechanism in addition to the existing HACA mechanism.





How to reduce soot formation

- **better mixing** (lean and premixed → no soot // safety?)
- higher temperatures
- longer residence time (longer combustor)
- additives
- other combustor concepts RQL, LPP
  RQL Rich burn / Quick mix / Lean burnout
  LPP Lean / Premixed / Prevaporized

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