AAE 538: Air-Breathing Propulsion

Lecture 19: Gas Turbine Combustion

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Overview

- In the last lecture, we took a fundamental look at flame stabilization processes and general combustor design.
- We are now going to take a look at two of the key challenges in gas turbine combustion engineering as well as the way we try to overcome them.
  - Pollutant Emissions
    - Chemical and Physical Mechanisms of Production
    - Reduction Strategies
  - Combustion Instability
    - Fundamental Mechanisms of Coupling
    - Mitigation and/or Avoidance

Photo credit: USAF (http://www.pbs.org/wgbh/nova/space/contrail-effect.html)

Pollutant Emissions

- In air-breathing systems, the oxidizer is diatomic oxygen residing in the earth's atmosphere
- In most engines, the fuels used are of the ____________________.
  - For combustion with air
    - We usually just assume that nitrogen acts as an inert species and does not contribute to the reaction. In doing so, we have to add (79/21) moles of nitrogen for each mole of oxygen because air is 79% N_2 and 21% O_2 by volume. Hence, our equilibrium chemical equation will look something like:

  - CO_2 and H_2O have not always been regarded as pollutants because they are natural products from the combustion of a hydrocarbon fuel. However, they do contribute to global warming.
    -
    -

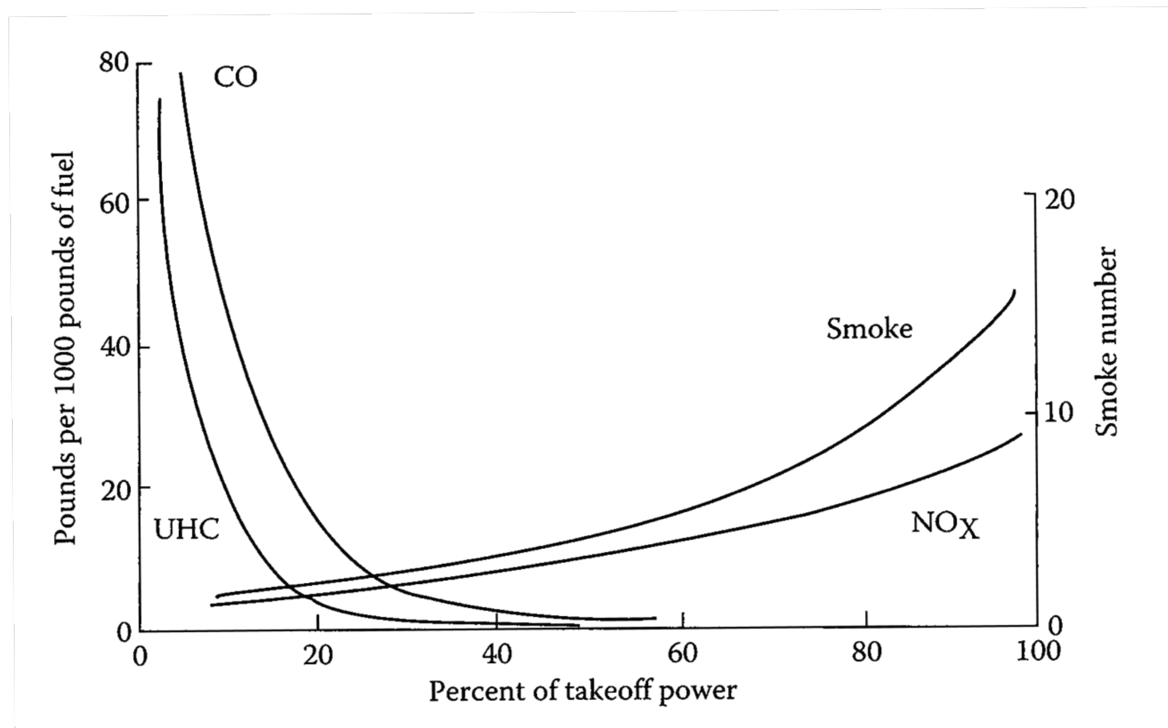
Pollutant Emissions

- The other (more hazardous) pollutants emitted from an engine's exhaust are:
  - Carbon Monoxide (CO)
    - _______________. Reduces the capacity for blood to absorb oxygen and , in high concentrations, can lead to asphyxiation and death.
  - Unburned Hydrocarbons (UHC)
    - _______________. Also can combine with NO_x to form photochemical smog
  - Particulate Matter (C)
    -
    - It's not normally considered to be toxic, at least at the levels emitted, but there have been links between asthma (and other similar respiratory diseases) with atmospheric pollutant concentrations of small particles on this scale.
    -
  - Oxides of Nitrogen (NO_x)
    - Toxic: contributes to the problem of photochemical smog, damages plant life, and contributes to acid rain. No acute effects on humans, but increased risk of respiratory disease.
  - Oxides of Sulfur (SO_x)
    - Toxic, corrosive, and leads to formation of sulfuric acid in the atmosphere

Pollutant Emissions

Production Mechanisms

- The concentration levels of pollutants in combustion flue can be related directly to the ______________________________ of the combustion process.
  - This is exactly the problem… These conditions vary significantly from one combustor to another and, for any given combustor, with changes in operating conditions.



Pollutant Emissions

Carbon Monoxide

- When a combustion zone is operating ____________________, large amounts of CO are formed because of the lack of oxygen that is present to complete the reaction to CO_2. In practice, CO emissions are found to be much high than predicted from equilibrium calculations:
  -
  - They are the highest when the rate of heat release and flame temperatures are low. This suggests that much of the CO is produced from incomplete combustion
    -
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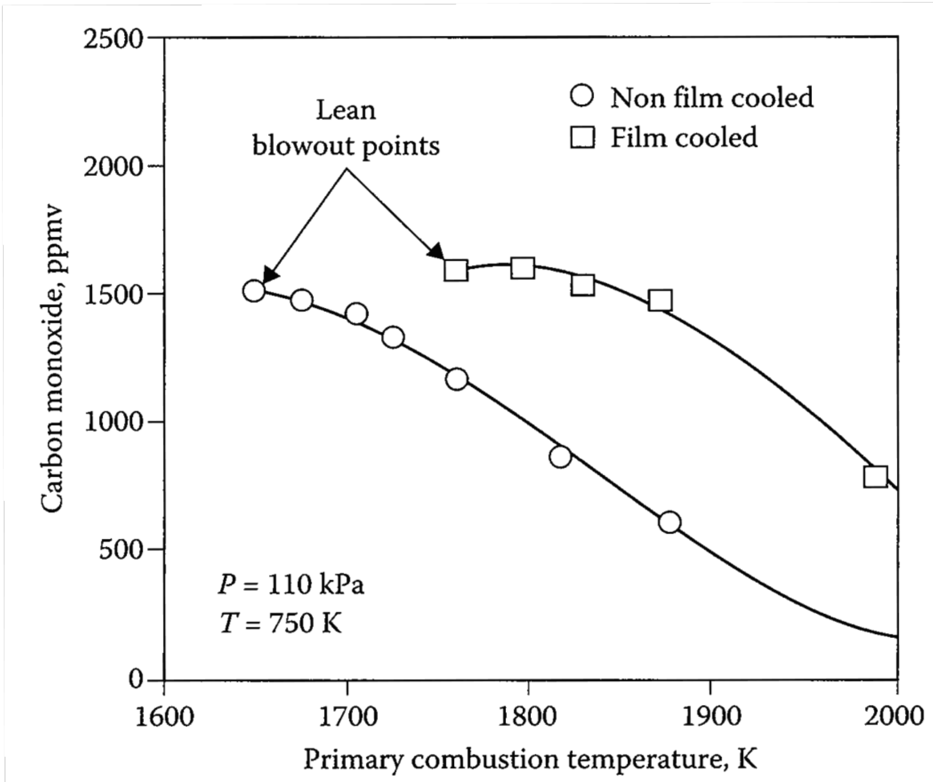
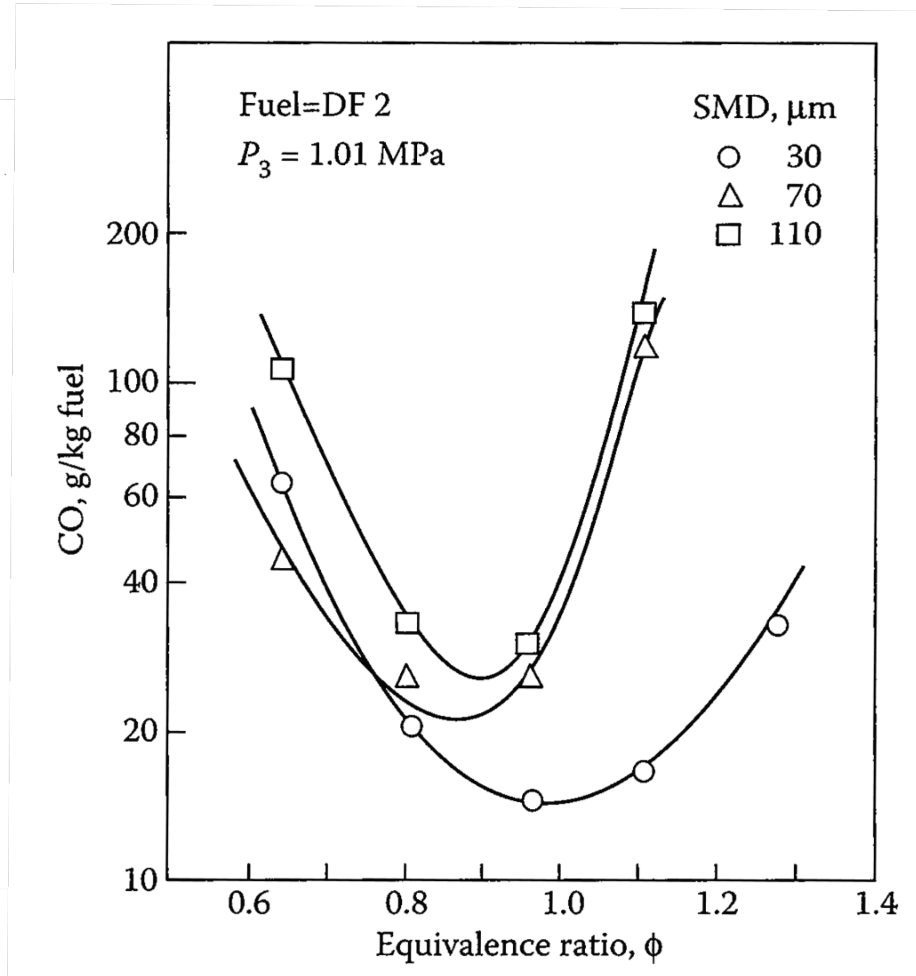
- Once CO is formed, it is relatively resistant to oxidation. It's usually even the rate-determining process in achieving complete combustion in many practical systems.
  - At high temperatures, the major reaction for removing CO is
  - At low temperatures, the major reaction for removing CO is

Pollutant Emissions

Carbon Monoxide





Pollutant Emissions

Unburned Hydrocarbons

- This pollutant can take the form of fuel itself that emerges from the combustor, or simply products of the thermal decomposition of the fuel into lower MW hydrocarbons.
- Typically associated with:
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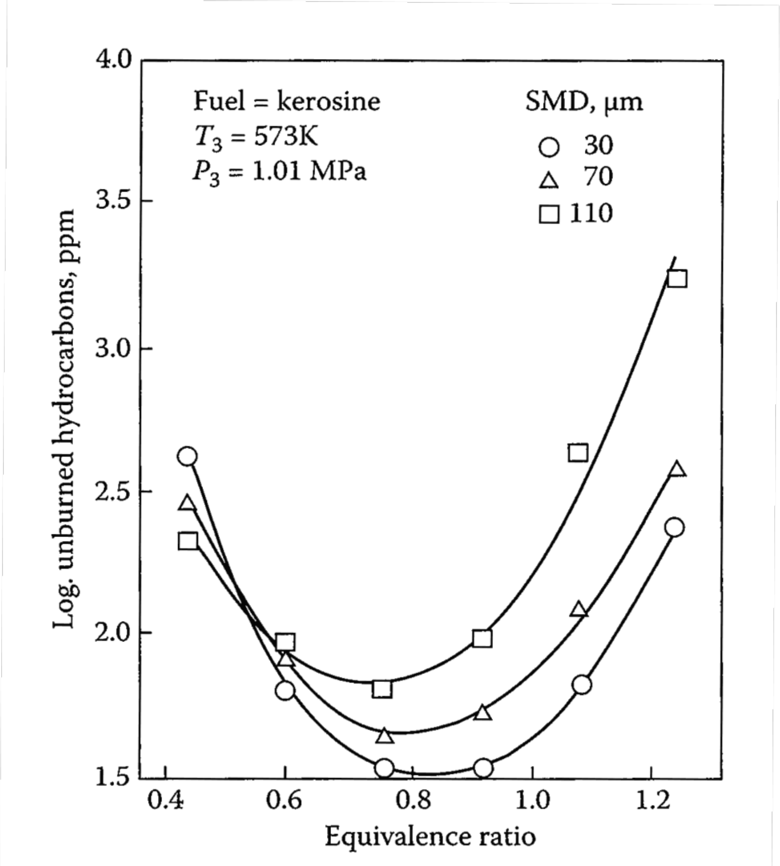
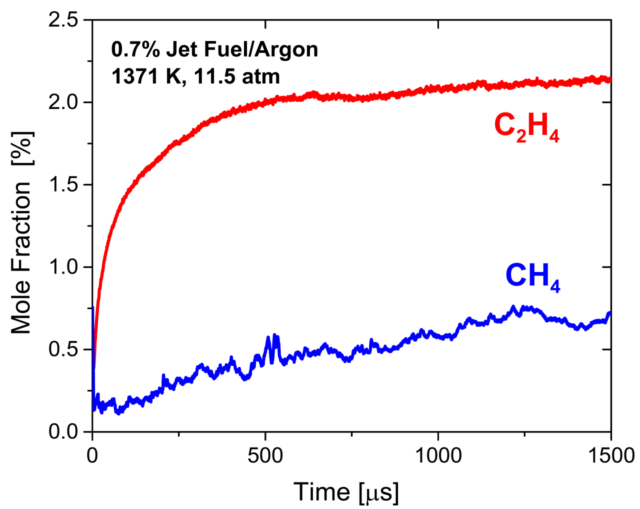
- The reaction kinetics are more complicated than for CO, but it is found that two respond to directly to the same changes in condition.



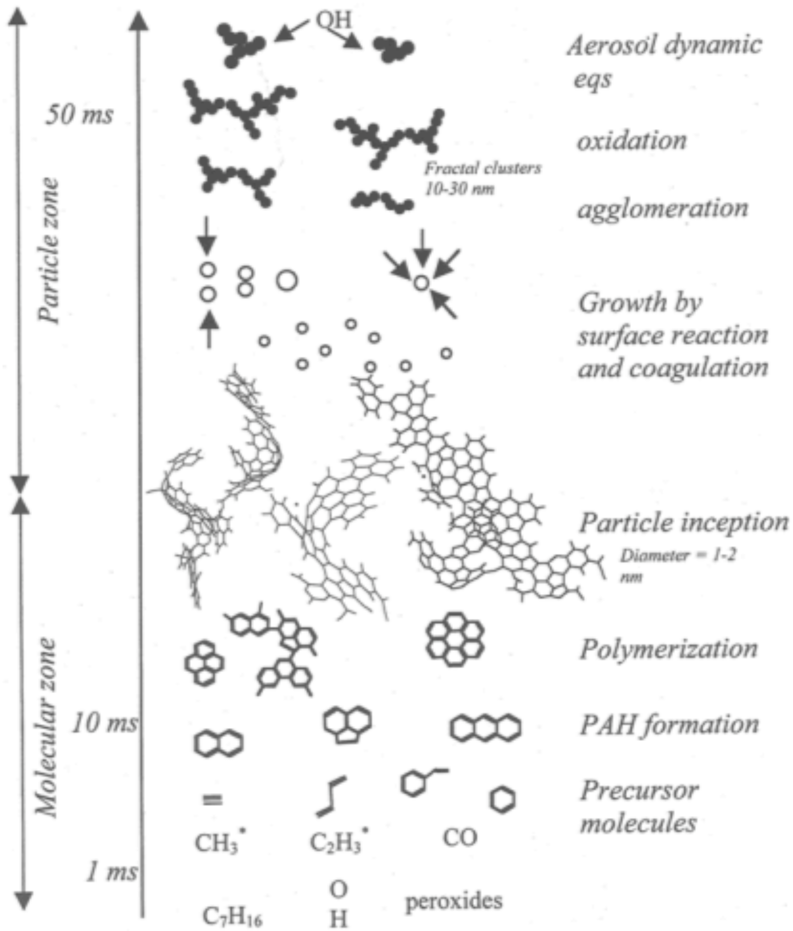


(above) measured UHC volume fractions for jet fuel combustion.

(left) Jet fuel combustion product yields from Davidson et al., 'Shock Tube Measurements of Jet and Rocket Fuels'

Pollutant Emissions

Soot



- The production of soot occurs __________ ____.
- These are the regions in which recirculating, burned products move upstream, then envelop some fuel vapor in an oxygen-deficient region at high temperature.
- Much of the soot produced in the primary combustion zone is actually consumed in the high temperature regions downstream, especially in R-Q-L combustors.
  -

Pollutant Emissions

Oxides of Nitrogen (NO_x)

- Most nitric oxide (NO) formed in combustion subsequently oxidizes into NO_2, so the two are typically lumped together in terms of NO_x, rather than NO.
- NO_x can be produced by four different mechanisms:
  -
  -
  -
  -
- Thermal NO is produced by the oxidation of atmospheric (diatomic) nitrogen in high temperature regions of the flame and post-flame gases.
  - The process is actually endothermic
  - The progress rate is only significant at temperature above
  - The Zeldovich mechanism:

Pollutant Emissions

Oxides of Nitrogen (NO_x)

- The NO_x production rate is extremely sensitive to temperature, once above $\approx 1850K$. Hence the total NO_x emission is going to be a function of temperature and time.
    -
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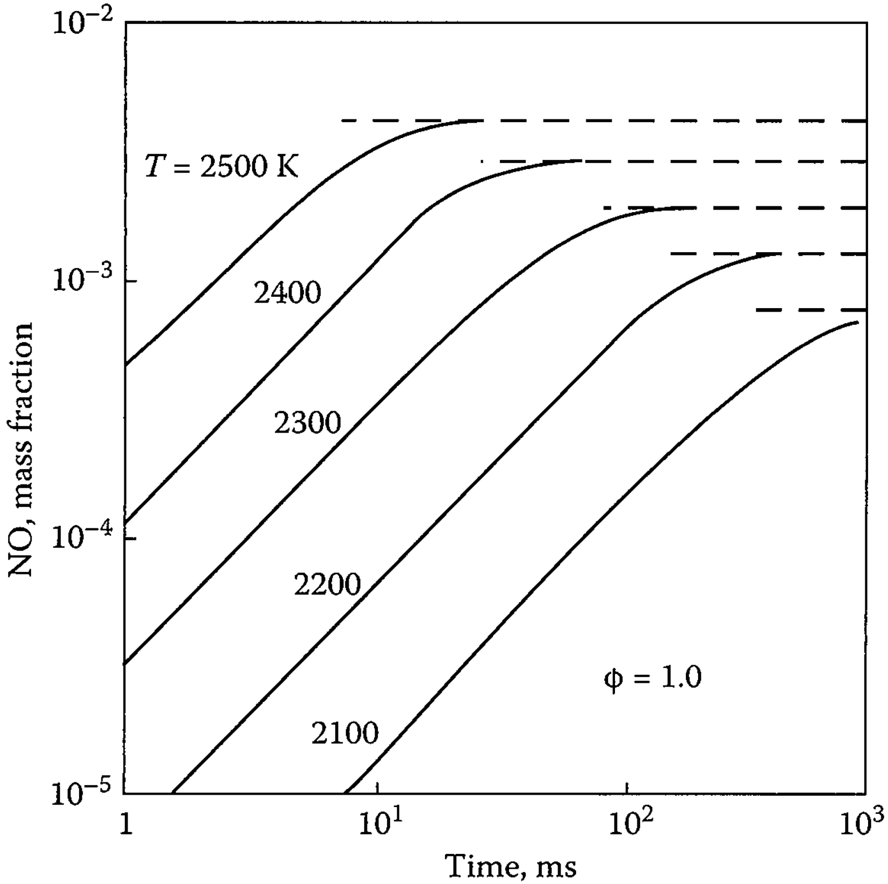


- For the typical conditions in a GT combustor (high temperature, ms residence times), NO will increase linearly with time, but won't necessarily reach an equilibrium value.
- For very-lean premixed flames, NO formation will be largely independent of residence time...

Pollutant Emissions

Oxides of Nitrogen (NO_x)

- The nitrous oxide mechanism is initiated by the reaction

$$N_2 + O \rightarrow N_2O$$

where the nitrous oxide (N_2O) formed is then oxidized to NO through the reactions

- Under certain conditions, NO can be found very early in the flame. This fact is, unfortunately, in direct conflict with our ideas of the kinetically–controlled processes in the previous two mechanisms. We understand the initiating reaction, in this case, as:

$$N_2 + CH \rightarrow HCN + N$$

Nicol et al. ASME 92-GT-115, 1992

Pollutant Emissions

Oxides of Nitrogen (NO_x)

- Here, the balance of the prompt NO mechanism involves the oxidation of the HCN molecules and the N atoms. Under lean-premixed conditions, this looks like:

  for the HCN molecule, whereas the N atom reacts mainly by the second Zeldovich reaction:

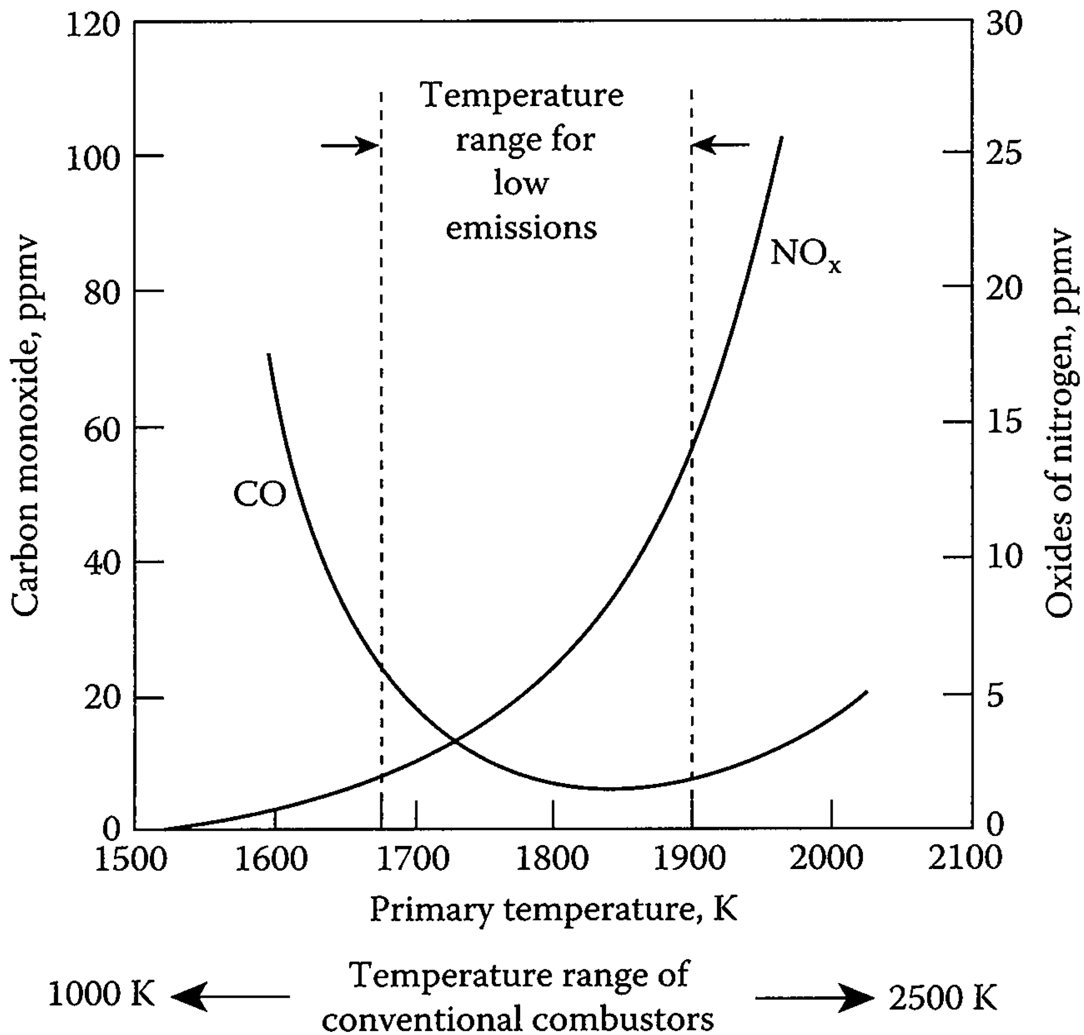
- Prompt NO_x becomes a primary concern ________________________________.

- Fuel NO_x production mechanisms stem from the presence of fuel-bound nitrogen (bonded to the organic molecule).
  - Heavy distillates can contain as much as 1.8%
  - This is typically a negligible mechanism of NO_x production.

Nicol et al. ASME 92-GT-115, 1992

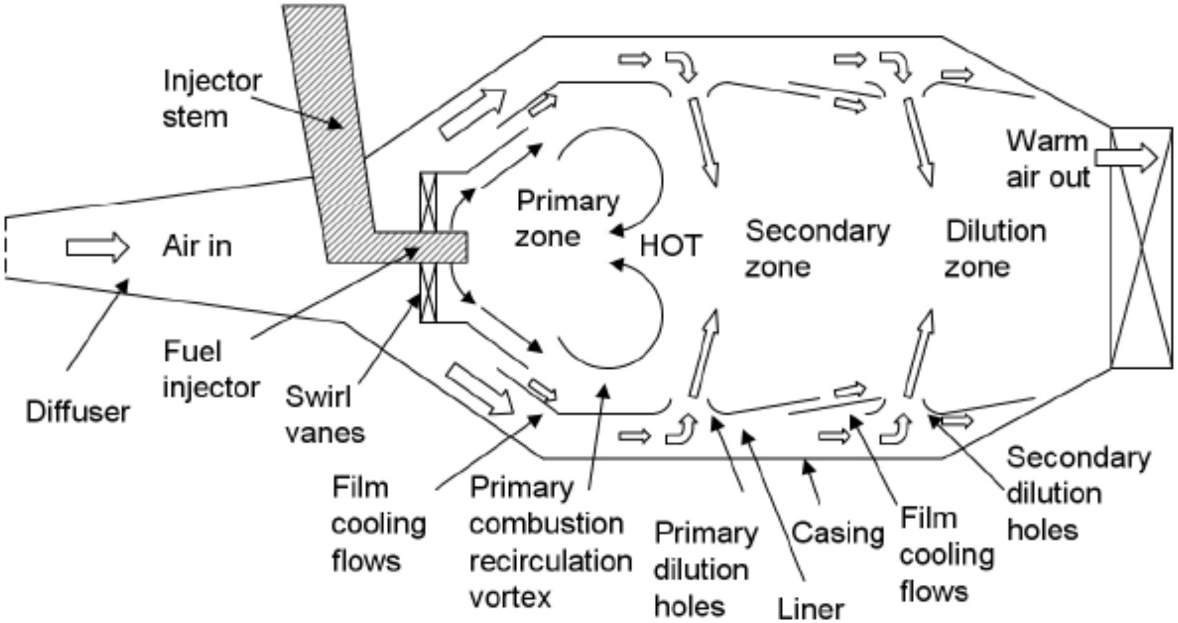
Pollutant Emissions

Oxides of Nitrogen (NO_x)



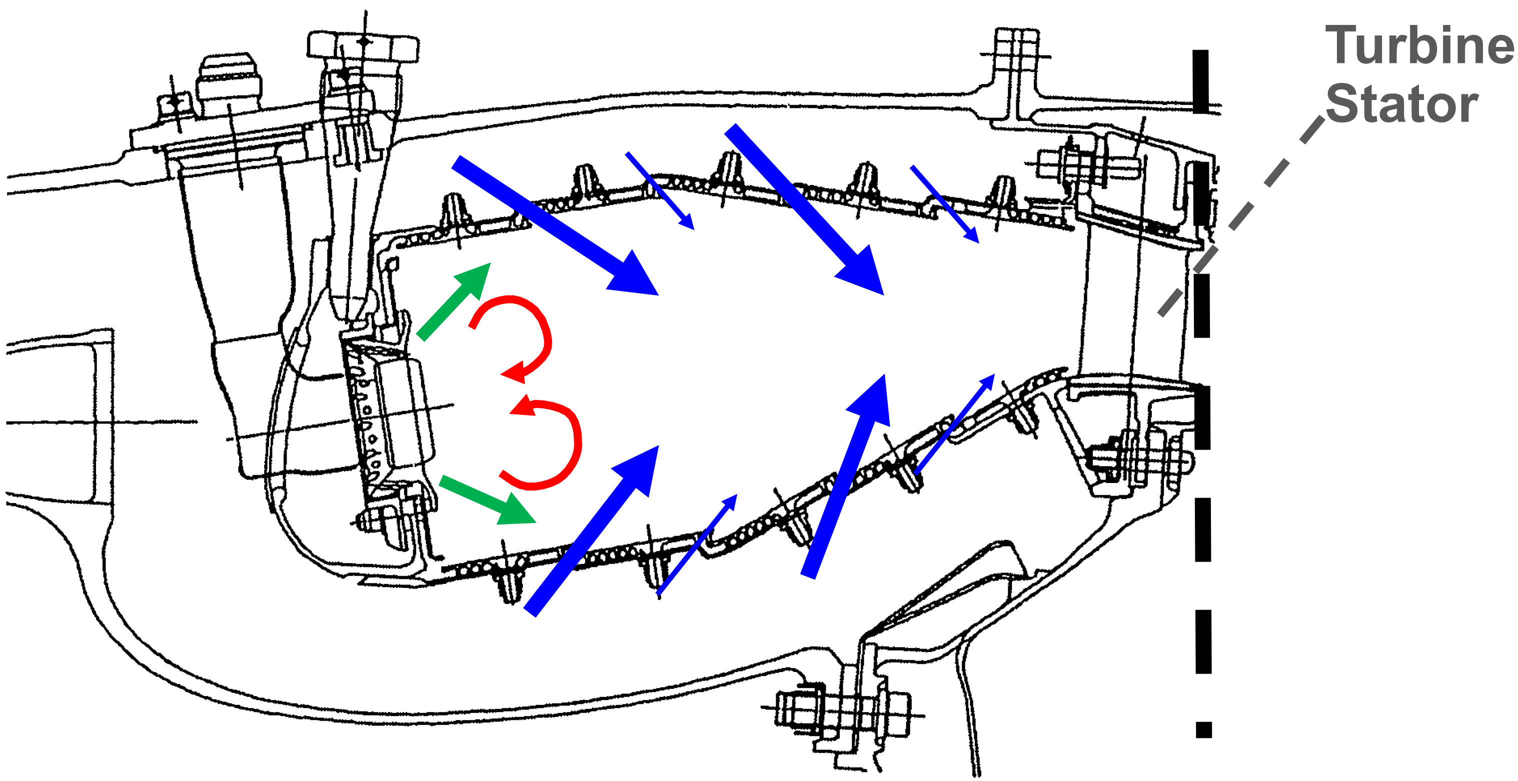
Legacy Gas Turbine Combustion

Design Orientation



Legacy Gas Turbine Combustion

Where Does Pollution Form?



Legacy Gas Turbine Combustion

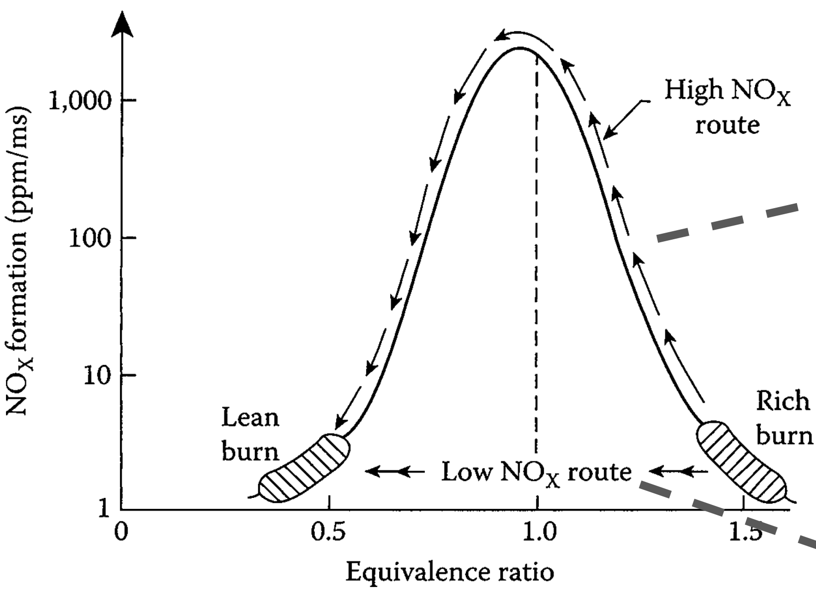
What can we do about it?

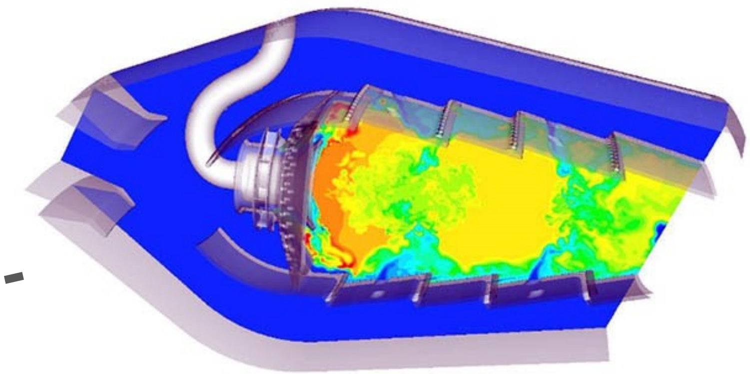
Legacy Gas Turbine Combustion

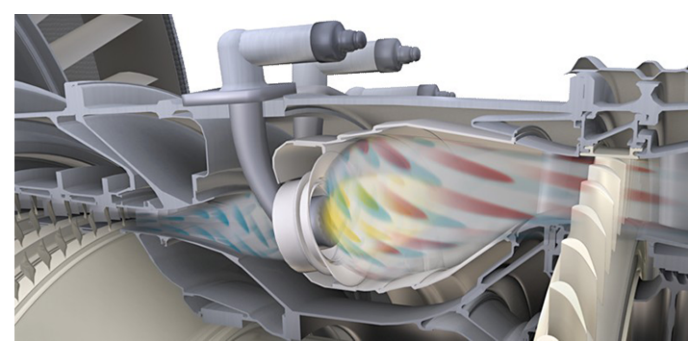
What can we do about it?

- To minimize NO_x, we need to minimize the rate of production and the residence time:

- This is where ______________________________ comes into the picture.

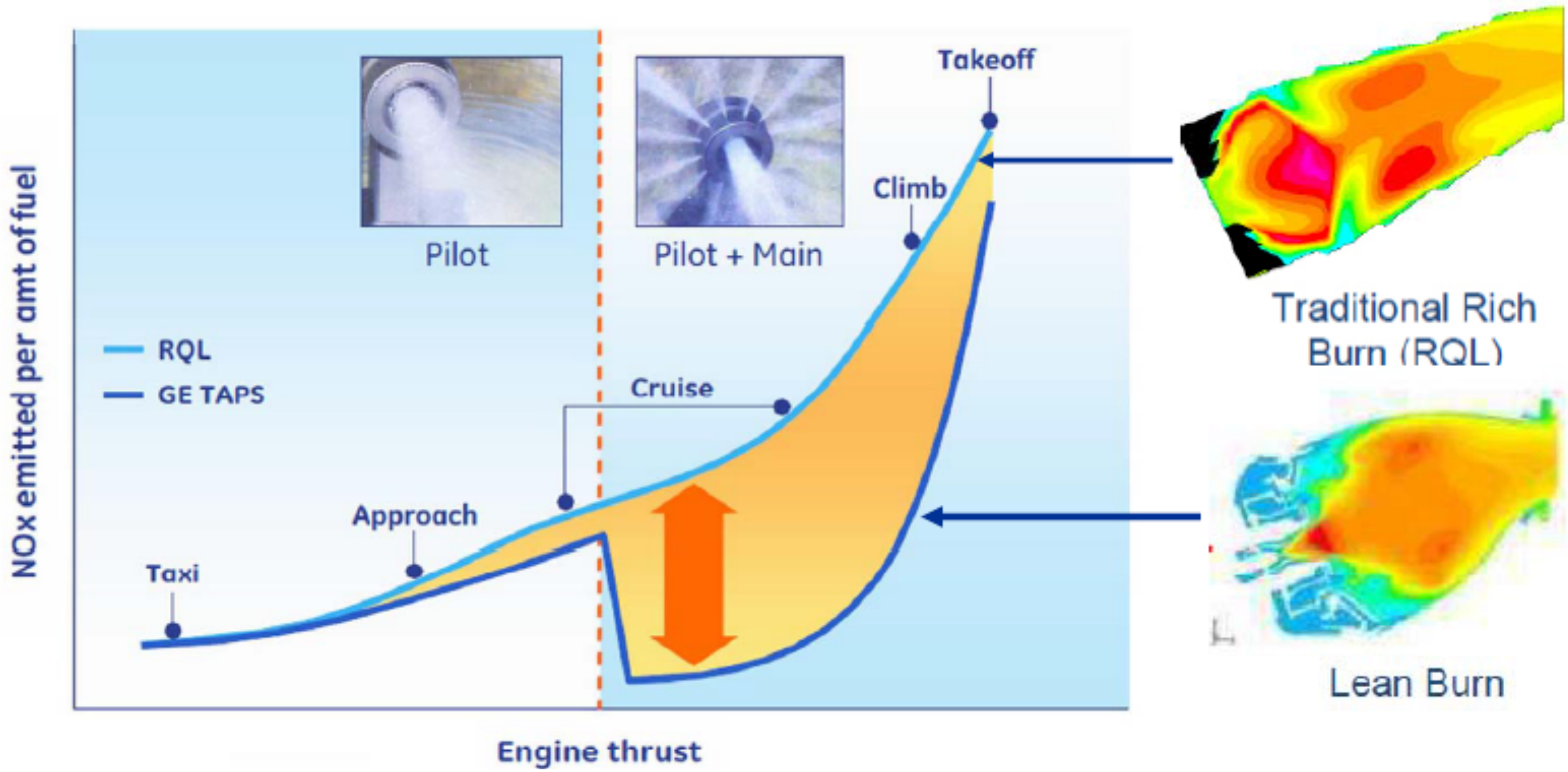




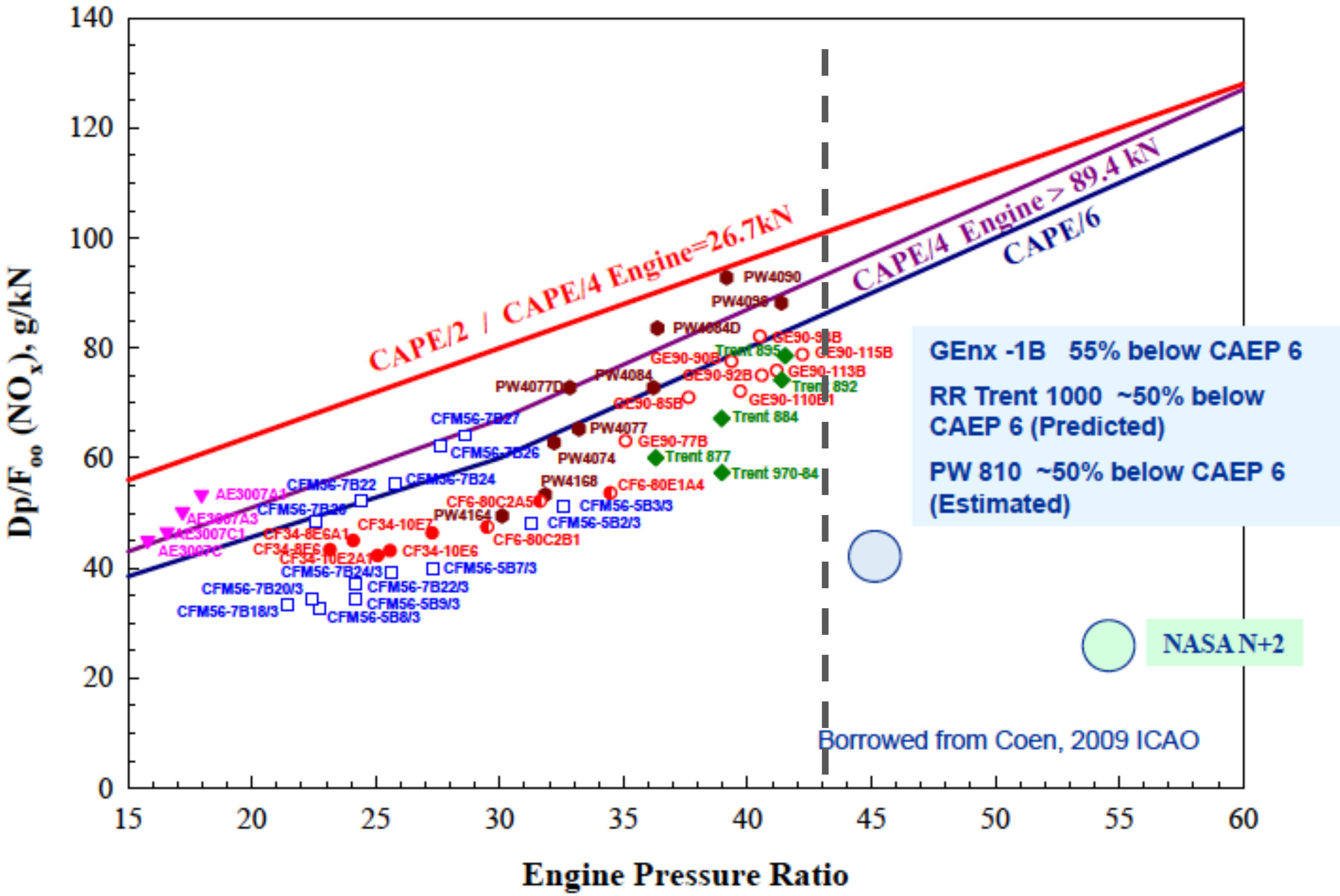


Lean Combustion

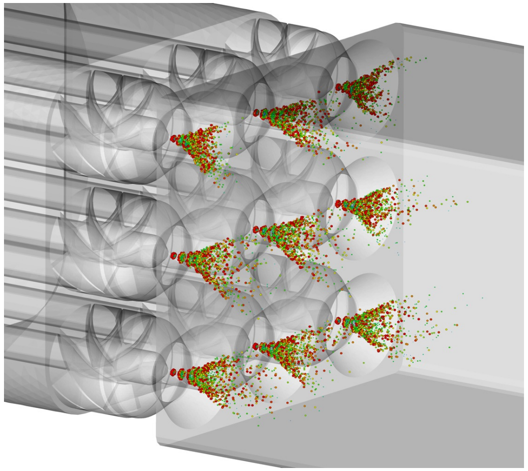
Straight from the GE Propaganda…

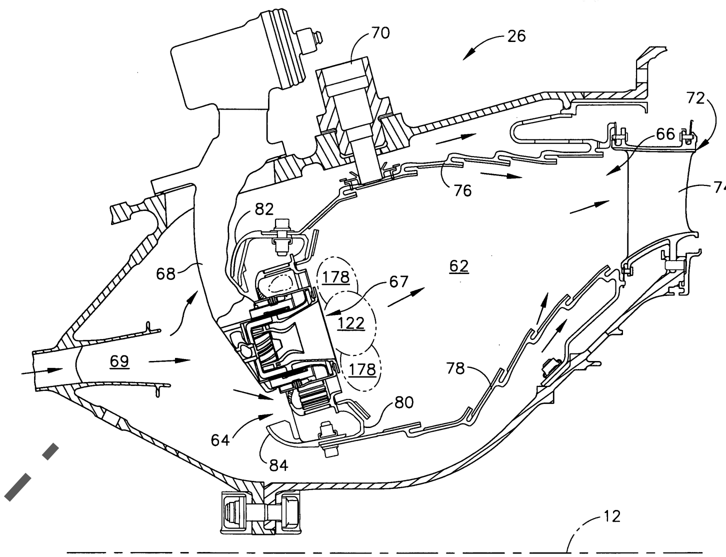


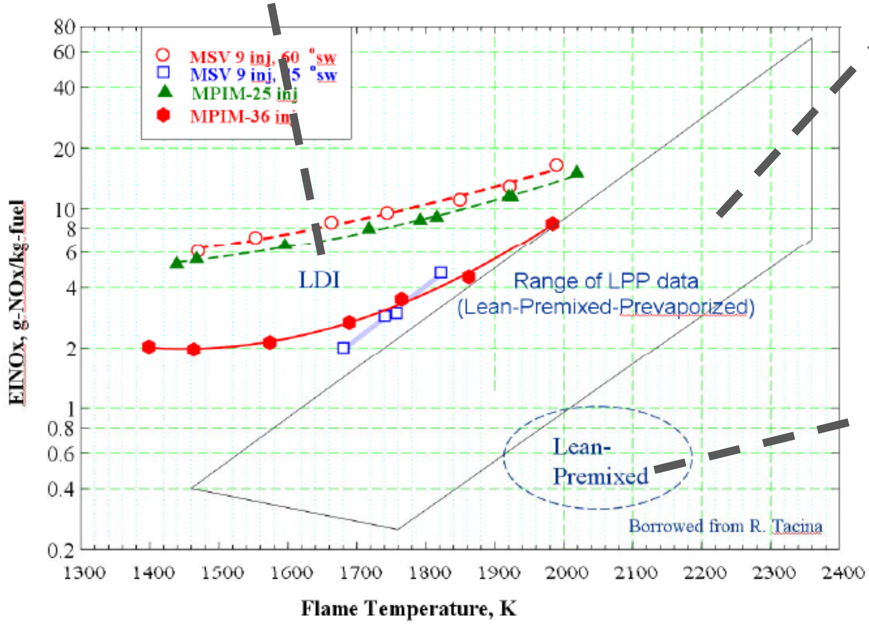
Current LTO NOx Emissions

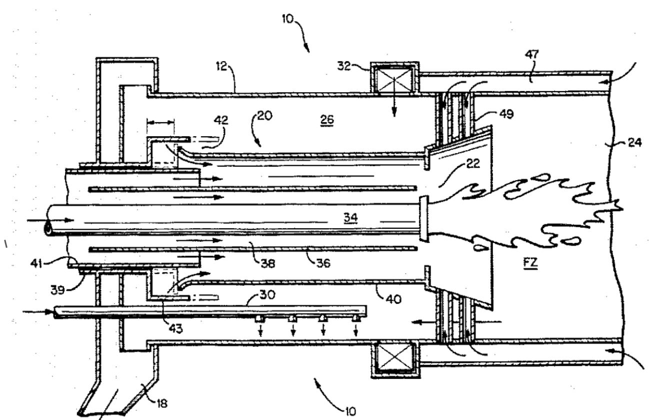


Impact of Combustion Scheme on NOx



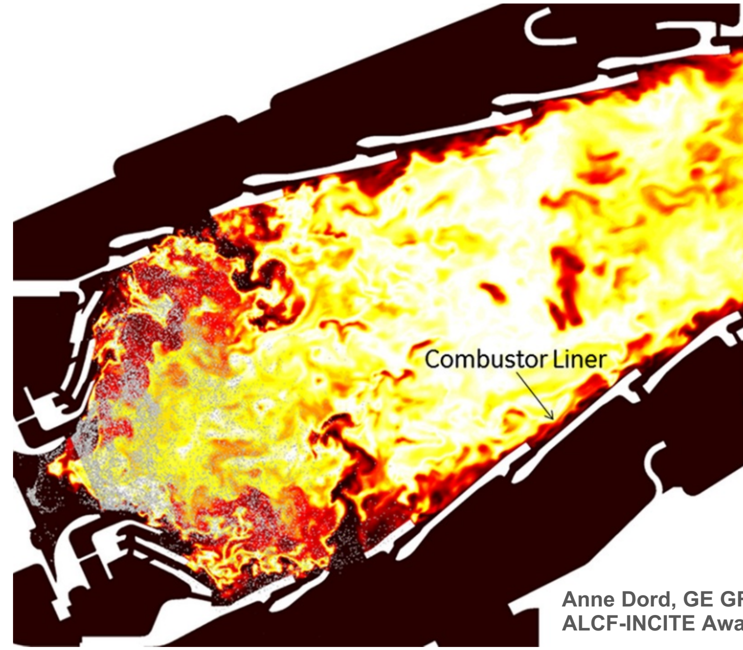




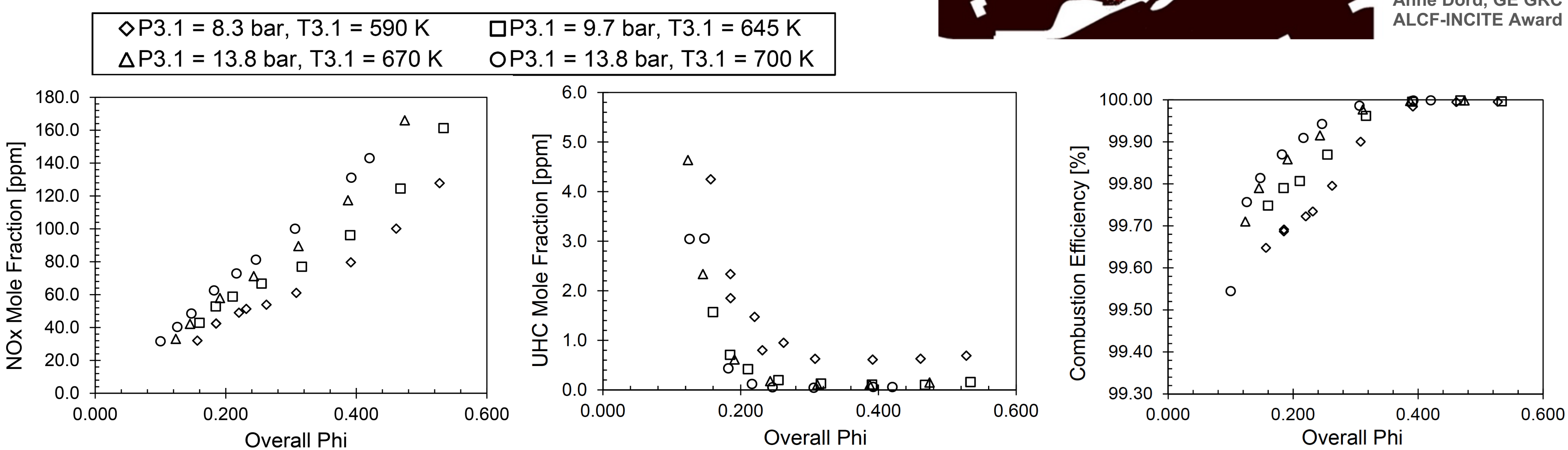


Lean Combustion

- From our discussions of NOx production mechanisms, it is now clear why lean combustion is a good idea.
  - How lean can we go before we run into other problems?
- ____________________ is a phenomena we observe in ultra-lean, high efficiency combustion systems
  - A drop in combustion efficiency
    - Increased CO and UHC
- Caused by localized loss of flame stabilization



Anne Dord, GE GRC
ALCF-INCITE Award



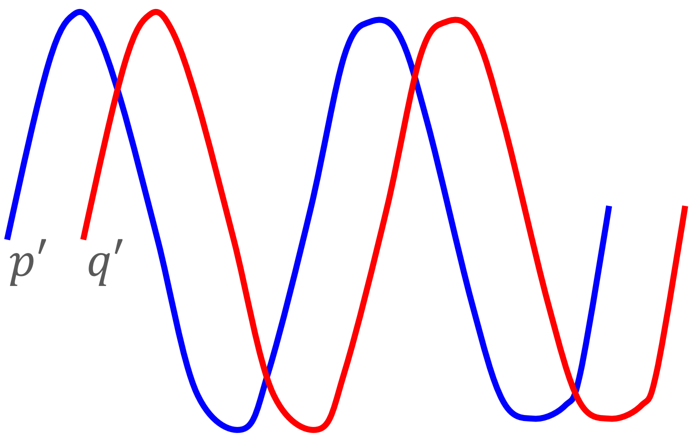
Combustion Instability

Thermo-acoustic coupling in lean combustors

- A combustion instability is a large-amplitude oscillation of one or more of the natural acoustic modes in a combustion chamber.
- Fundamentally, these instabilities are caused by multi-physics coupling between the pressure fluctuations (p') characteristic of acoustic modes of the chamber and (some other) characteristically-unsteady process in the flame.
  - Given that the flame is sensitive to the dynamics of the fluid flow, there exists an implicit feedback between fluctuations in the flame heat release (q') and (p').

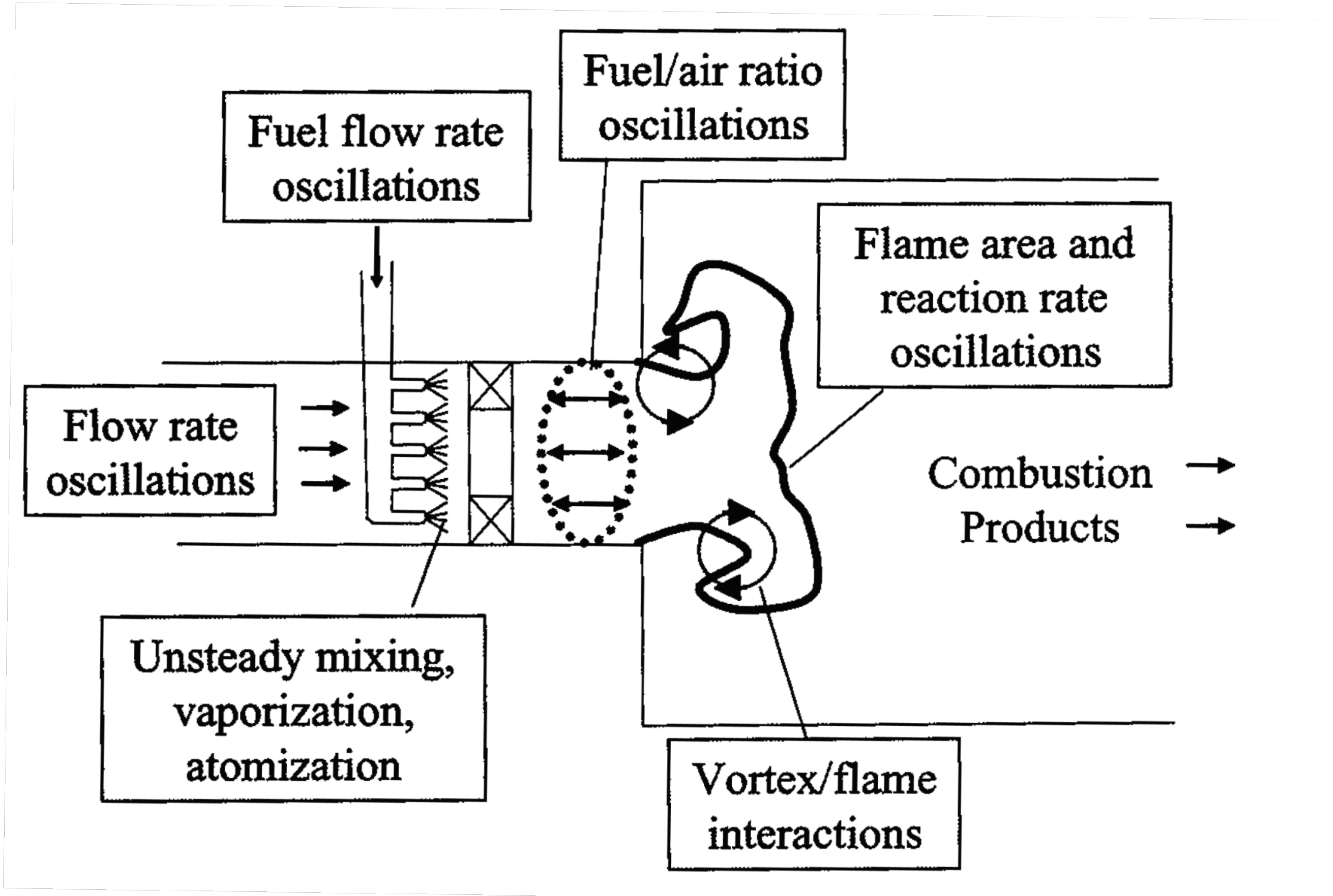
Combustion Instability

- Self-amplification occurs when the flame adds energy to the acoustic field. This condition is defined by Rayleigh's criteria.



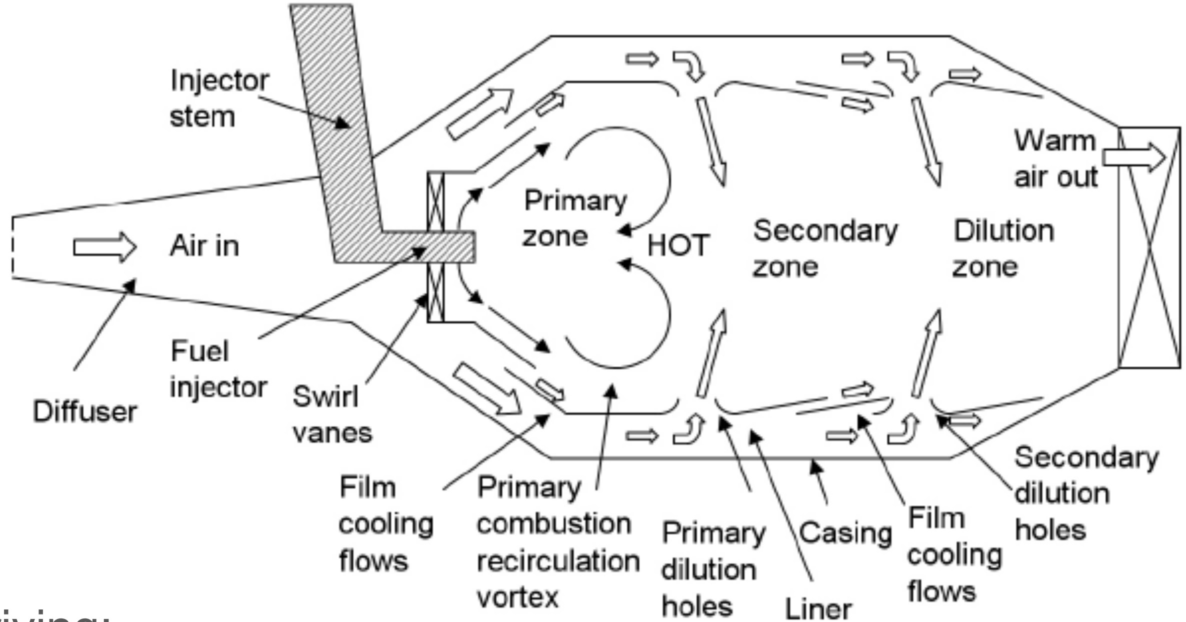
- Oscillations will otherwise be damped by viscosity, heat transfer, sound radiation, etc.

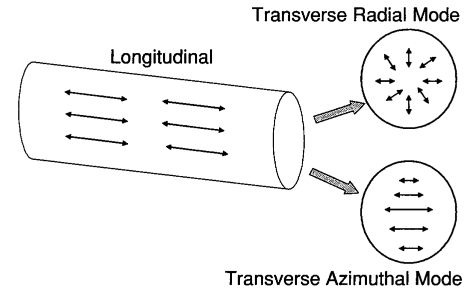
Combustion Instability



Lieuwen and Yang

Combustion Instability



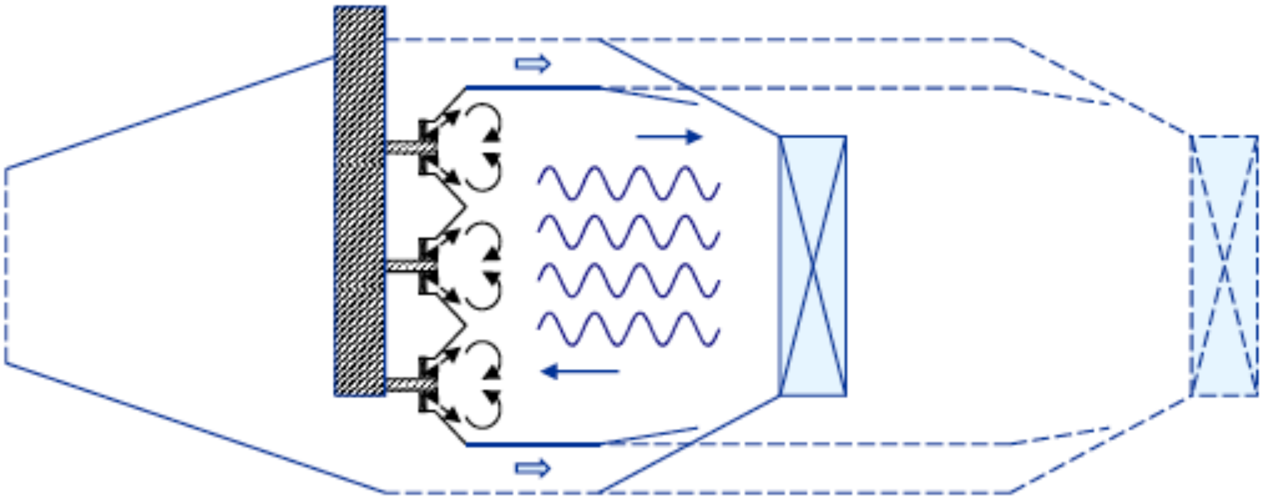


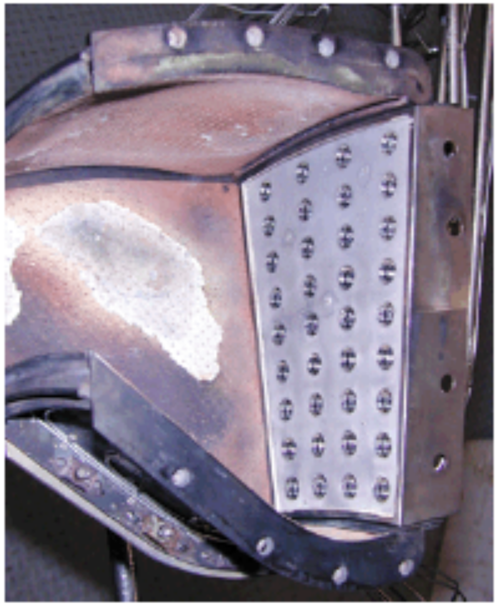
- Driving:

- Damping:

Combustion Instability

Lean burning combustors are more susceptible



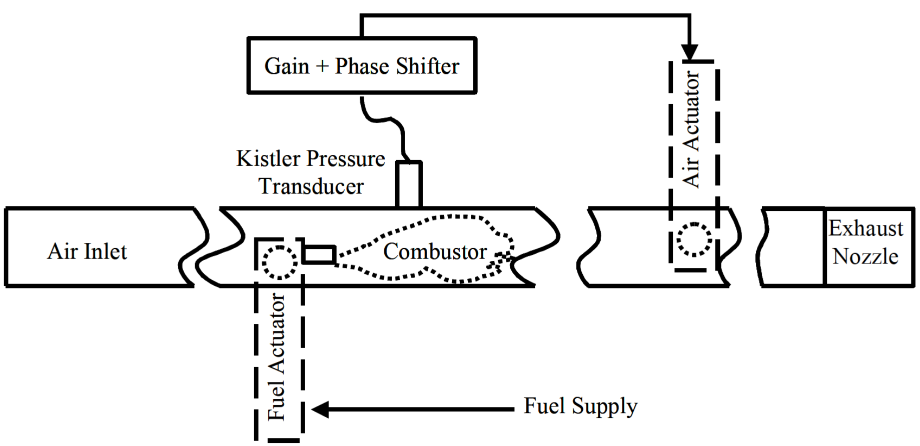


- Higher performance fuel injection and mixing
- Minimal (no) dilution air
- Reduced film cooling
- More uniform temperature distribution
- Shorter combustor

Combustion Instability Mitigation

- Tuning length scales and time-scales to get create destructive interferences, instead of amplification.

- Reactant flow modulation (fuel or air) to create a phase cancellation.



Zinn et al.