

US Gas Turbine R&D

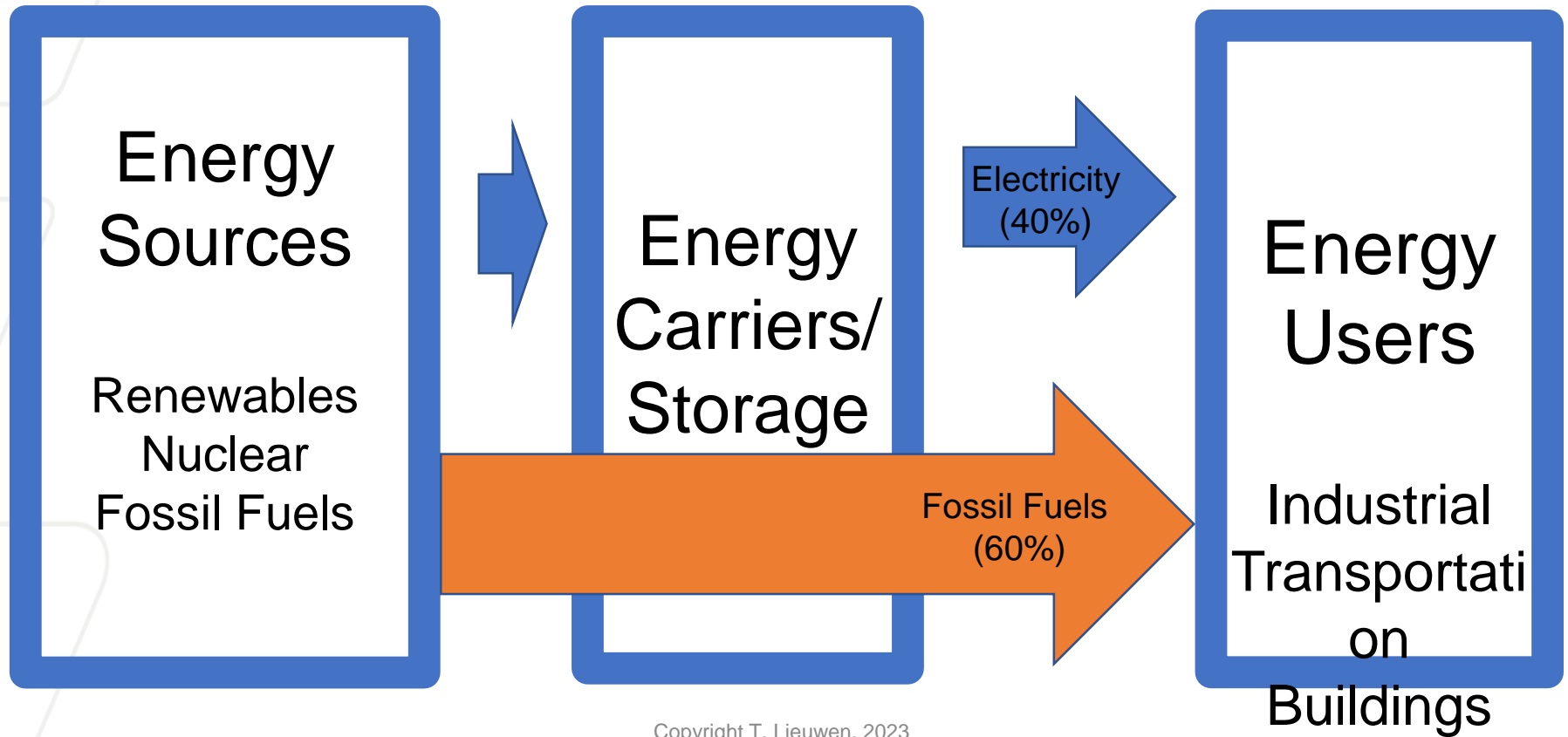
Operability, Emissions, Efficiency

Tim Lieuwen

Regents' Professor and David S. Lewis, Jr., Chair

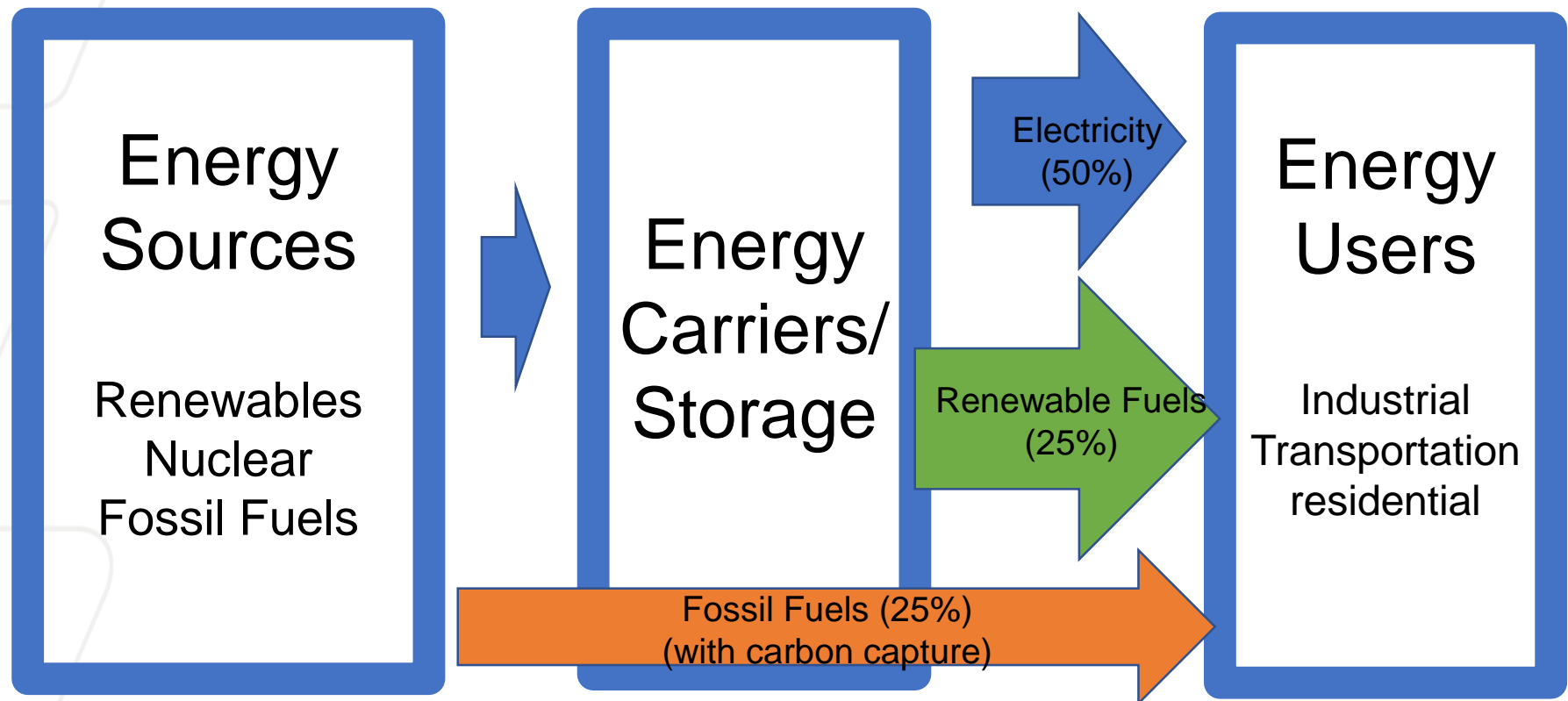
Executive Director, Strategic Energy Institute

US Energy System



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US Energy System – What will the net-zero CO₂ system look like?

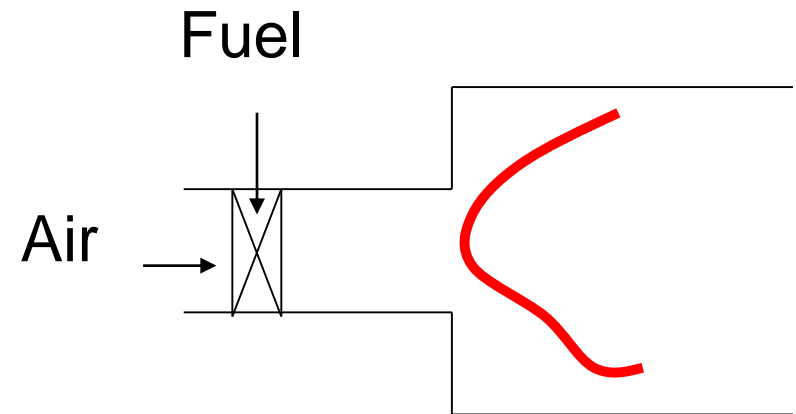


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*Source: Jesse Jenkins,
Princeton University*

Overview of R&D Work

- Cycle innovations
 - Oxyfuel – Allam, etc.
 - Air breathing – Efficiency
 - Carbon capture
- Combustor:
 - Operability
 - Pollutant emissions
 - Fuel flexibility
 - Turndown
- Turbine
 - Increasing TIT, life



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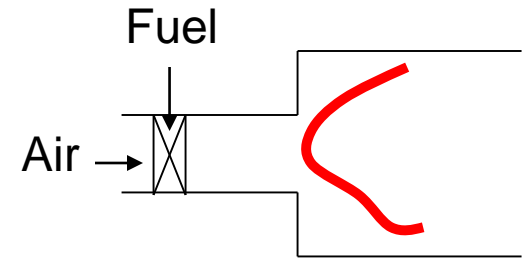
H₂ Work



Premixed vs Non-Premixed Flames

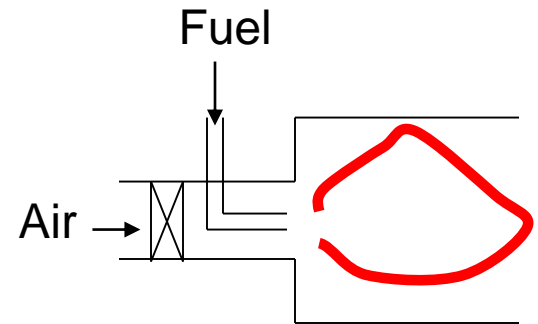
- Premixed flames

- Mixture stoichiometry at flame can be controlled
- Method used in low NO_x gas turbines



- Non-premixed flames

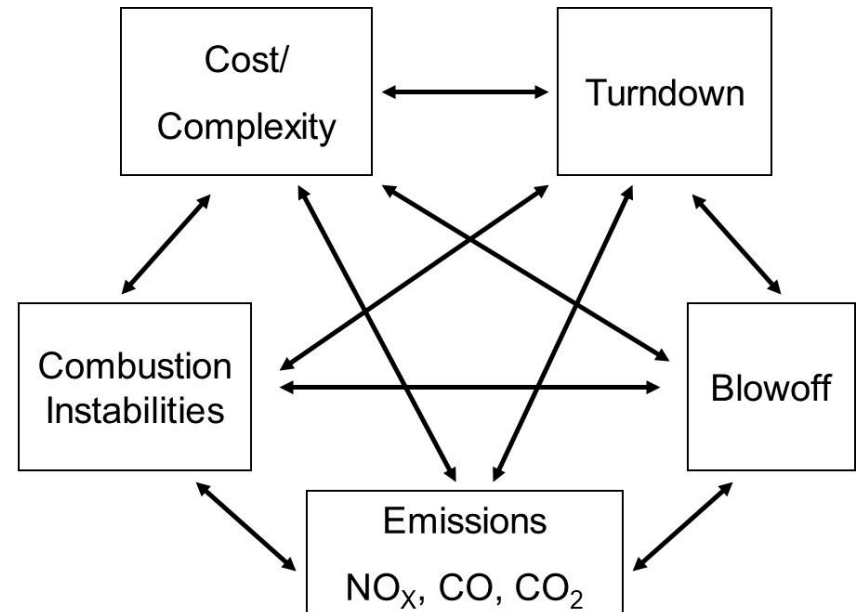
- Fuel and air separately introduced into combustor
- Mixture burns at $\phi=1$
 - i.e., stoichiometry cannot be controlled
 - Hot flame, produces lots of NO_x and soot (if burning a hydrocarbon)



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Combustor/Fuel Interactions

- Operability:
 - Blowout ("static stability")
 - Flashback and autoignition
 - Combustion Instability ("dynamic stability")
- Pollutant Emissions



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Combustor/Fuel Interactions

- Operability:
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- Pollutant Emissions
- Fuel Flexibility
 - $\text{H}_2/\text{CH}_4/\text{NH}_3$ blending

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Blowoff

- Low NO_x /high velocity/low pressure make flame stabilization more problematic



NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION



Industry Advisory June 26, 2008

Background:

On Tuesday February 26th, 2008, the FRCC Bulk Power System experienced a system disturbance initiated by a 138 kV transmission system fault that remained on the system for approximately 1.7 seconds. The fault and subsequent delayed clearing led to the loss of approximately 2,300 MW of load concentrated in South Florida along with the loss of approximately 4,300 MW of generation within the Region. Approximately 2,200 MW of under-frequency load shedding subsequently operated and was scattered across the peninsular part of Florida.

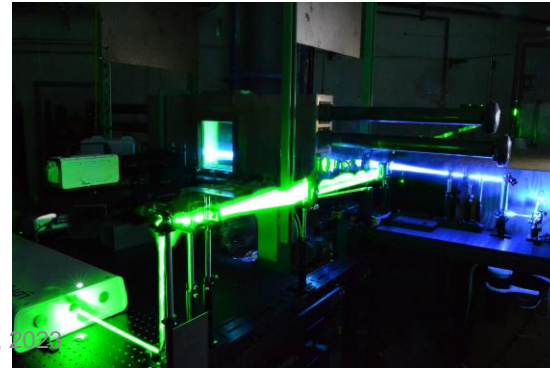
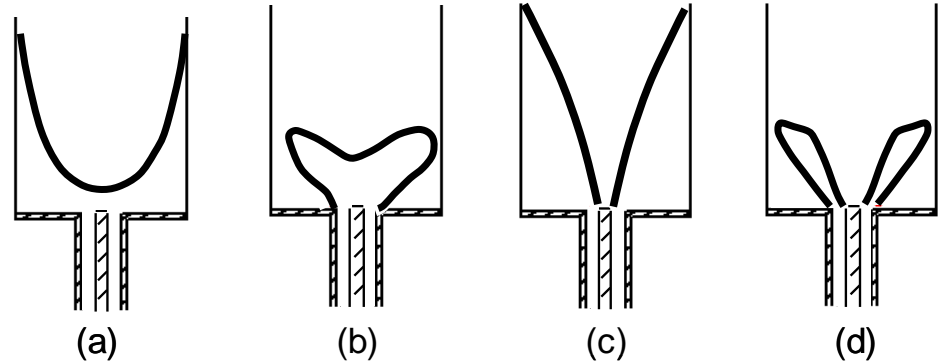
Indications are that six combustion turbine (CT) generators within the Region that were operating in a lean-burn mode (used for reducing emissions) tripped offline as result of a phenomenon known as “turbine combustor lean blowout.” As the CT generators accelerated in response to the frequency excursion, the direct-coupled turbine compressors forced more air into their associated combustion chambers at the same time as the governor speed control function reduced fuel input in response to the increase in speed. This resulted in what is known as a CT “blowout,” or loss of flame, causing the units to trip offline.

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Flame Stabilization and Blowoff

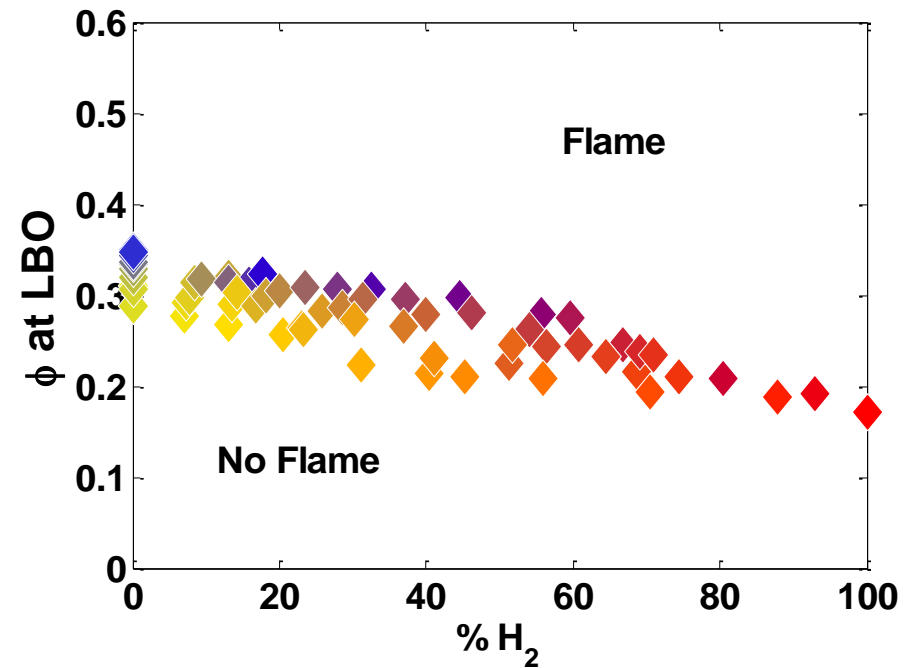
- Flame shapes controlled by local flame stabilization phenomenon
 - Controls combustion instability, heat loading, etc.



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Blowoff

- H_2 addition significantly extends blowoff limits



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Combustor/Fuel Interactions

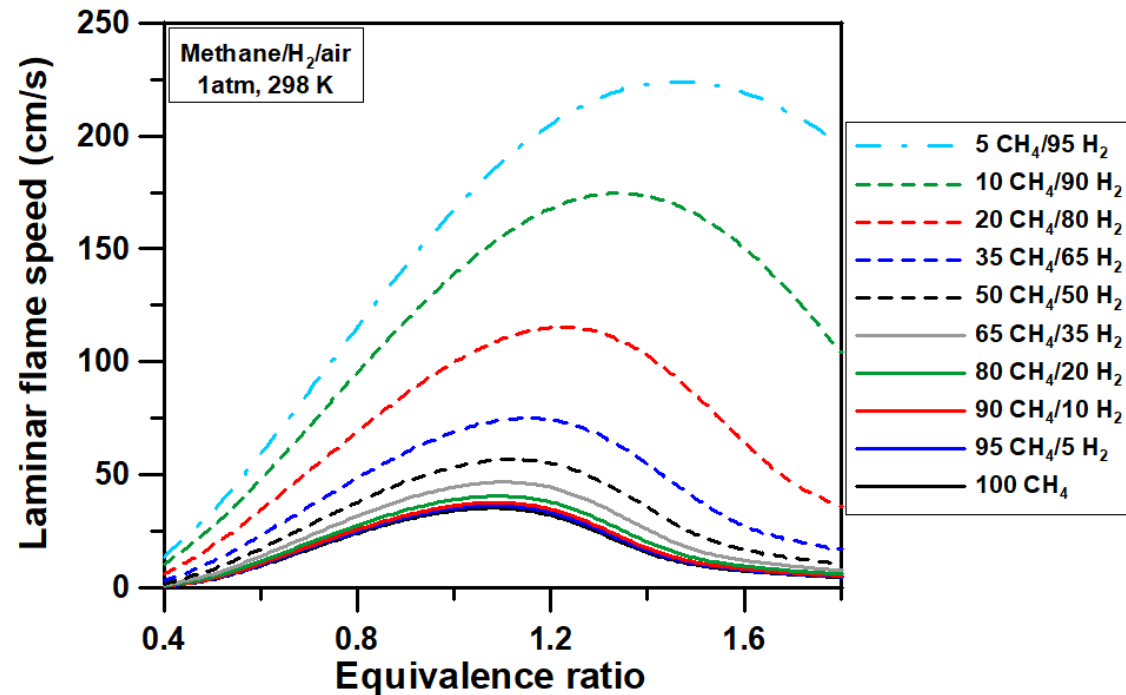
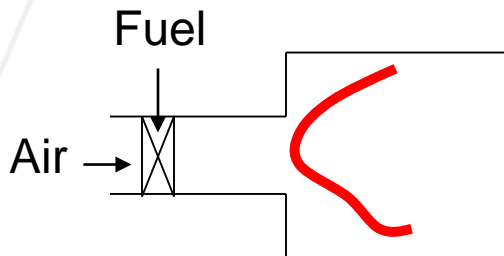
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Flashback

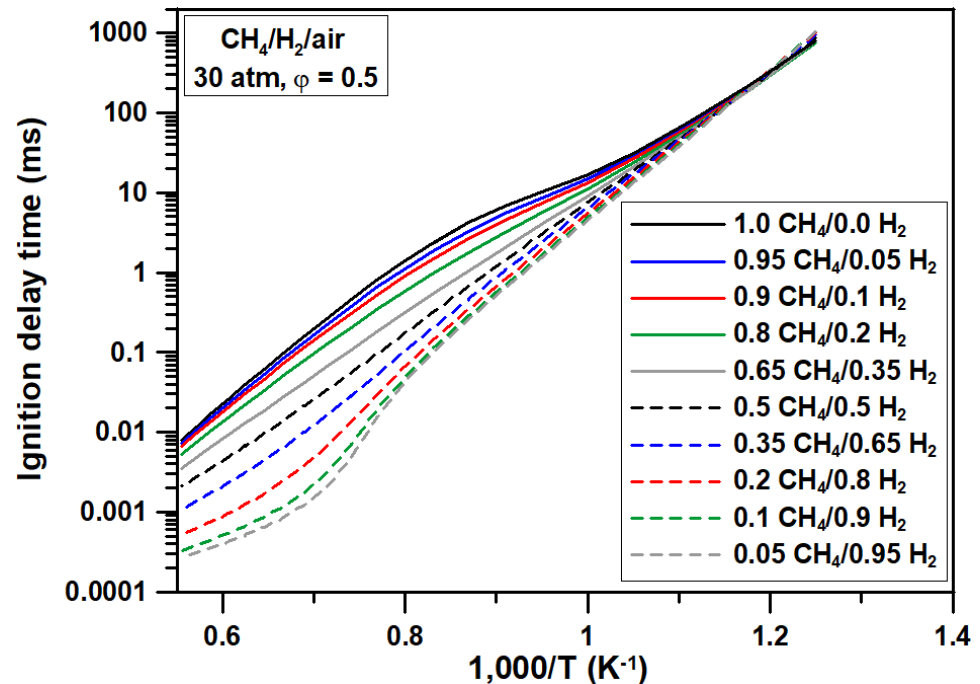
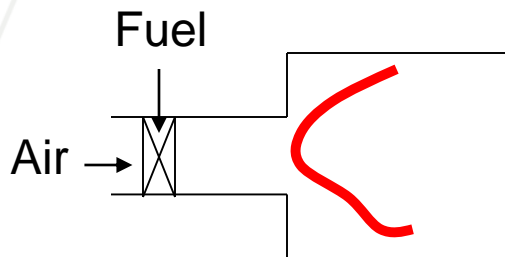
- Upstream propagation of a premixed flame into a region not designed for the flame to exist
- Several mechanisms exist for this to happen



Pressure of 1 atm and initial temperature of 298 K. Data courtesy of E. Petersen and Mathieu
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Autoignition

- Spontaneous ignition of mixture in upstream region not designed for the flame to exist
 - Occurs when autoignition time is shorter than premixer residence time



Equivalence ratio of 0.5 and pressure of 30 atm

Courtesy of E. Peterson and Mathieu

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Combustor/Fuel Interactions

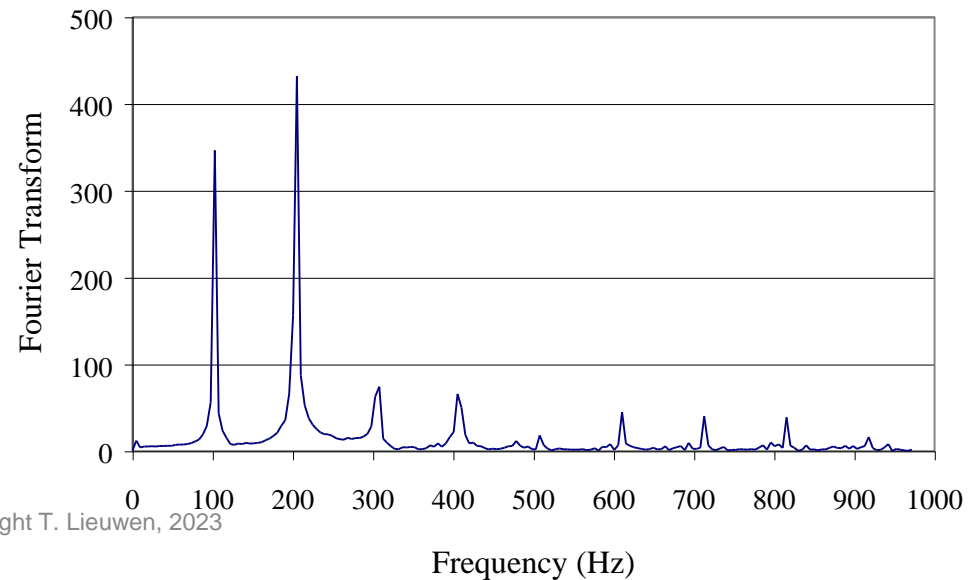
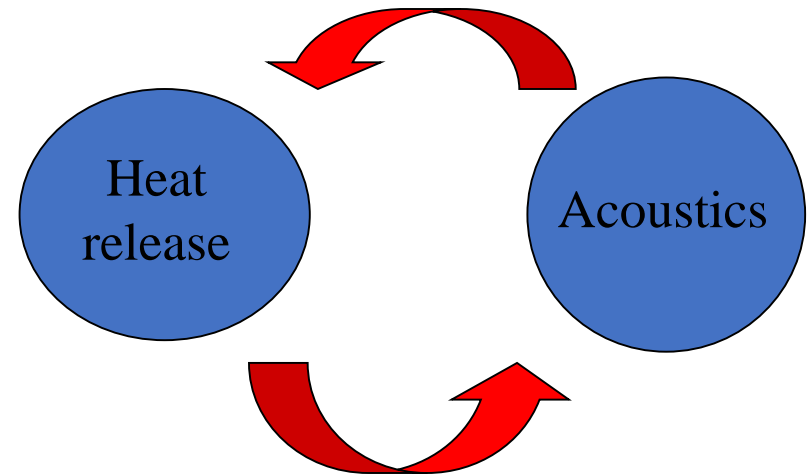
- Operability:
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Basic Feedback Cycle

- Large amplitude acoustic oscillations driven by heat release oscillations
- Oscillations occur at specific frequencies, associated with resonant modes of combustor

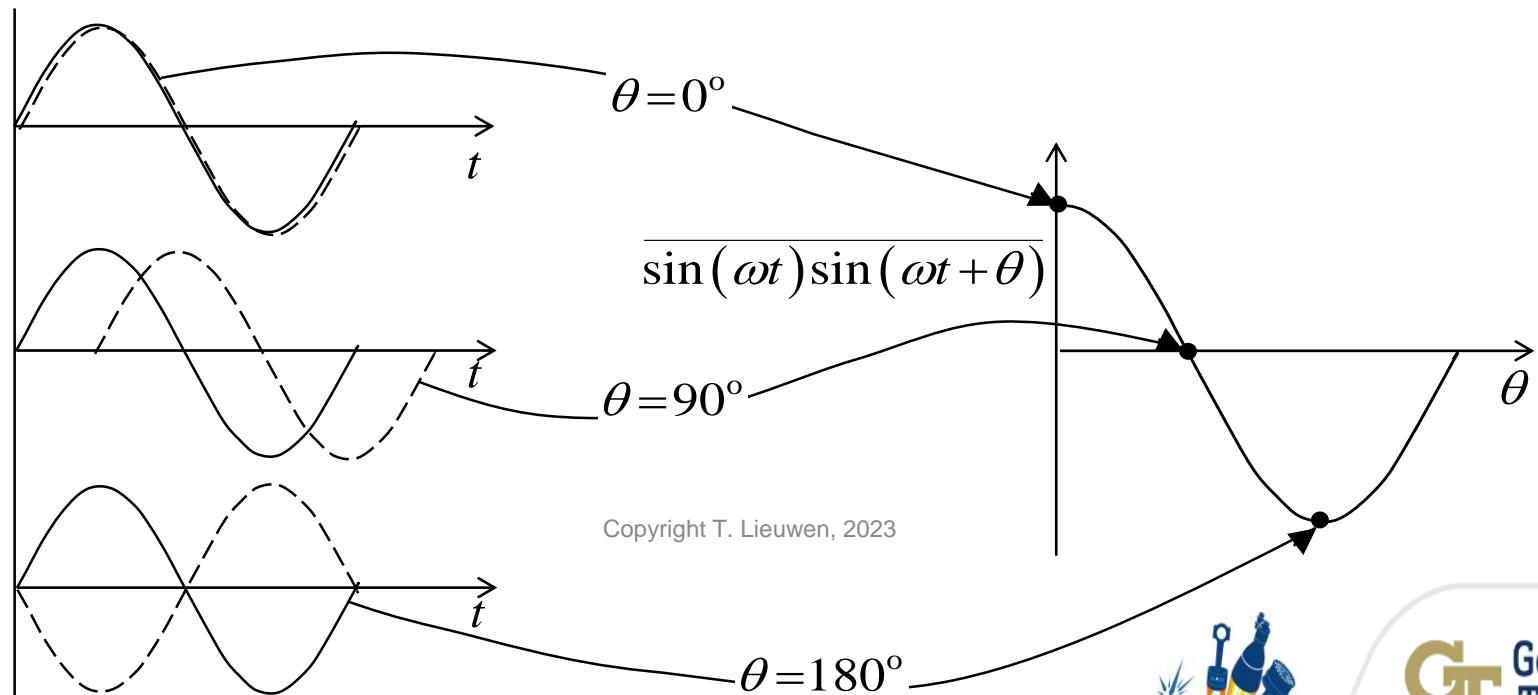


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Rayleigh Criterion and Combustion Amplification of Sound

- Combustion source term: $\Phi_{\Lambda} = \frac{(\gamma - 1)}{\gamma p_0} p_1 \dot{q}_1$
- Time average of product of two fluctuating quantities depends on phasing

$$\overline{\sin(\omega t) \sin(\omega t + \theta)} = \frac{1}{2} \cos \theta$$



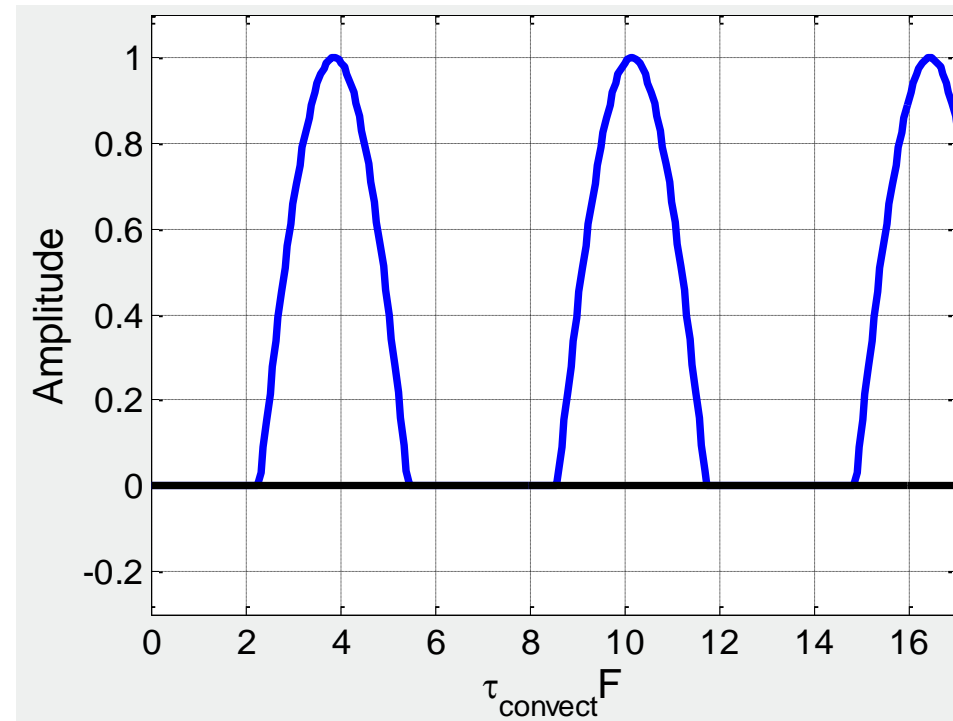
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Combustion instabilities do not exhibit monotonic dependence upon fuel or operating conditions

- Instabilities can occur when:

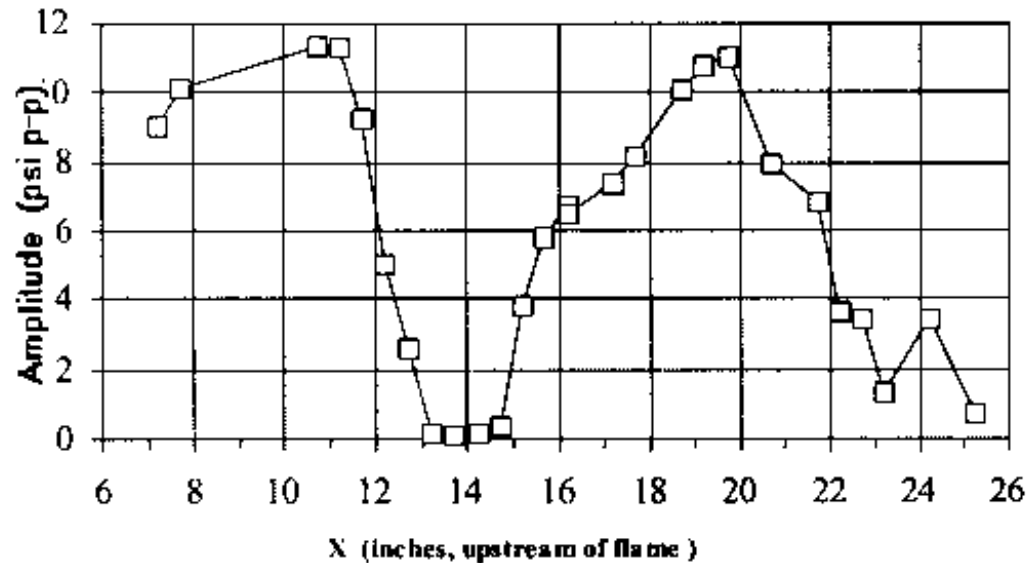
- $\cos(t_{\text{convect}} F) > 0$

- t_{convect} = time required for mixture to convect from fuel injection point to flame
- F = natural combustor frequency



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Example: Fuel Injector Location



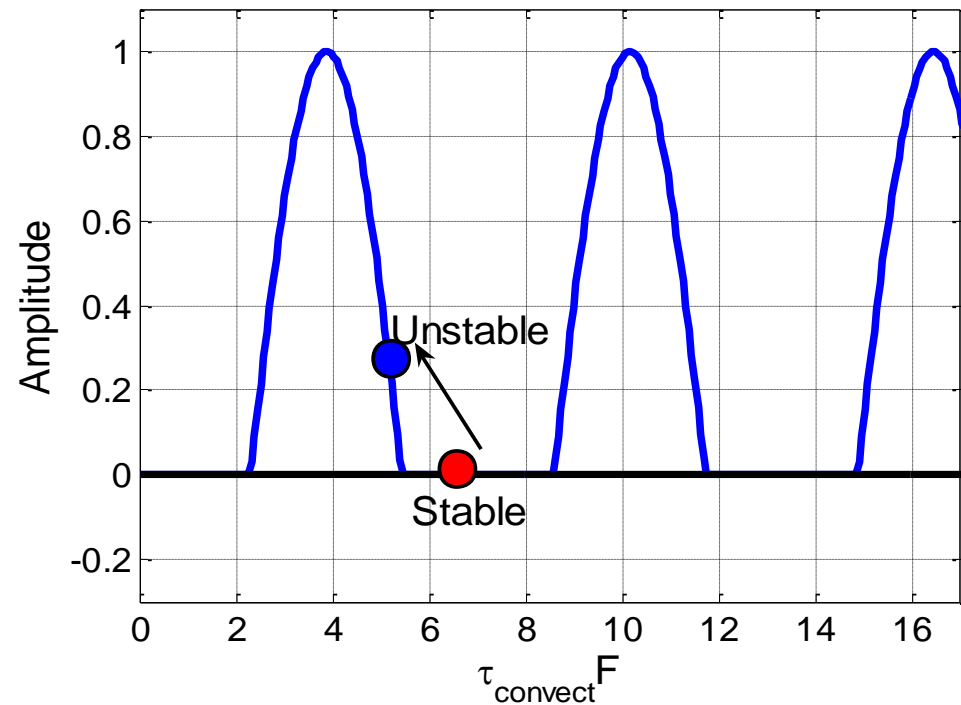
- Similar examples for combustor length, fuel/air ratio, H₂ fraction in fuel, etc.

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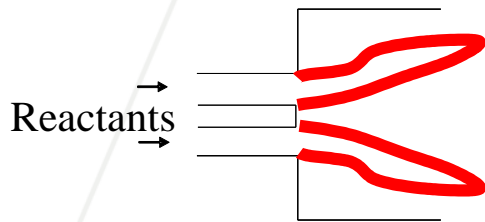
From Lovett, J., and Uznanski, K., Prediction of Combustion Dynamics in a Staged Premixed Combustor, ASME Paper # 2002-GT-30646

Example: H₂ addition to Natural Gas

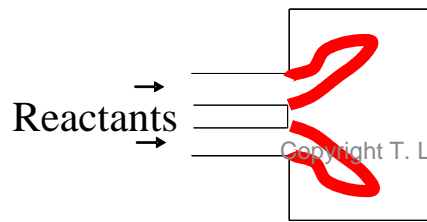
- Key effect of H₂ on dynamics is through alteration of flame shape/location



Condition 1



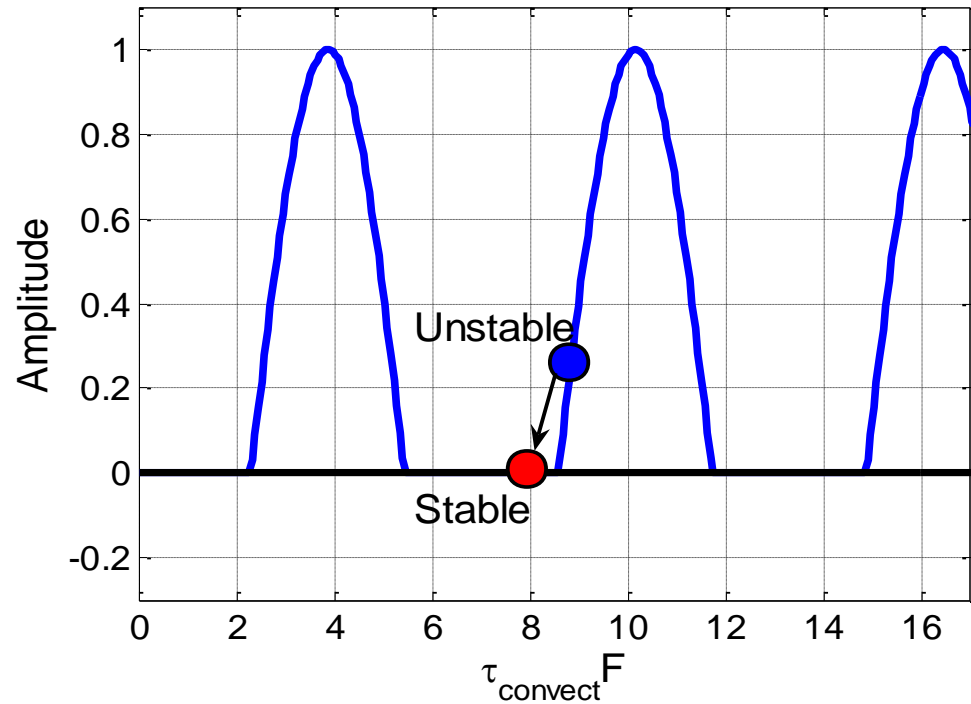
Condition 2



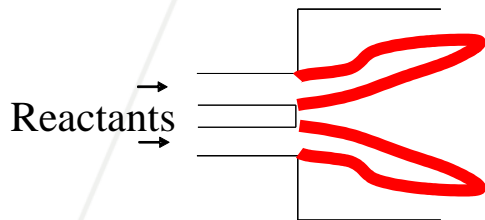
Example where dynamics made worse

Example: H₂ addition to Natural Gas

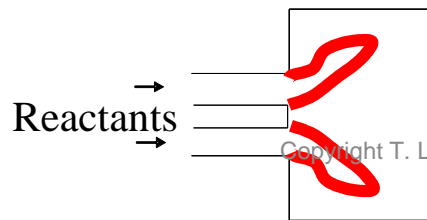
- Key effect of H₂ on dynamics is through alteration of flame shape/location
- Cannot make definitive comments on whether dynamics will be “better” or “worse” with H₂, except for near LBO dynamics



Condition 1



Condition 2



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Example where dynamics
made better

Combustor/Fuel Interactions

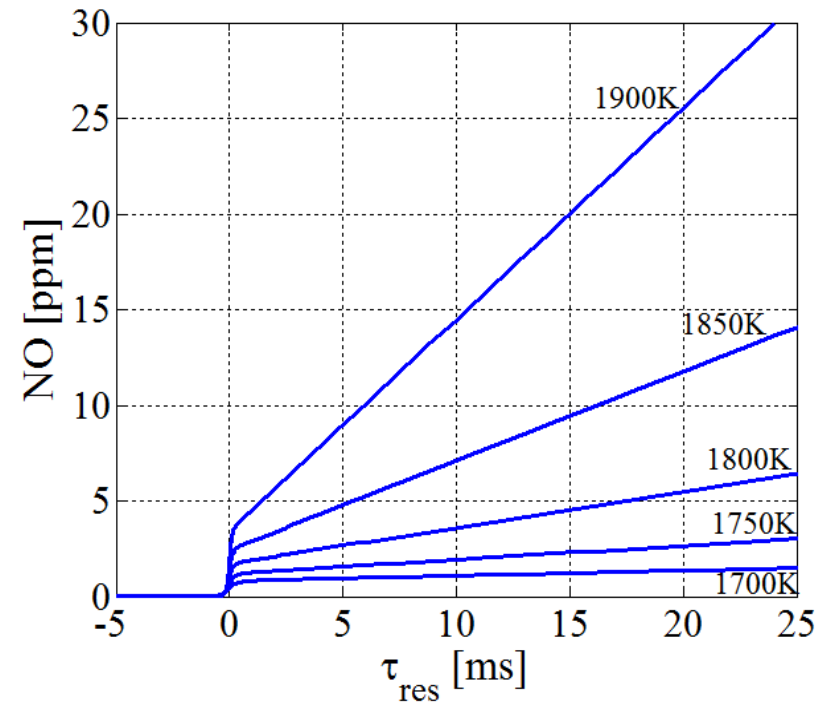
- Operability:
 - Blowout (“static stability”)
 - Flashback and autoignition
 - Combustion Instability (“dynamic stability”)
- Pollutant Emissions
 - NO_x
 - CO
 - Soot/particulates
 - SO_x

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NO_x Emissions – Basic Considerations

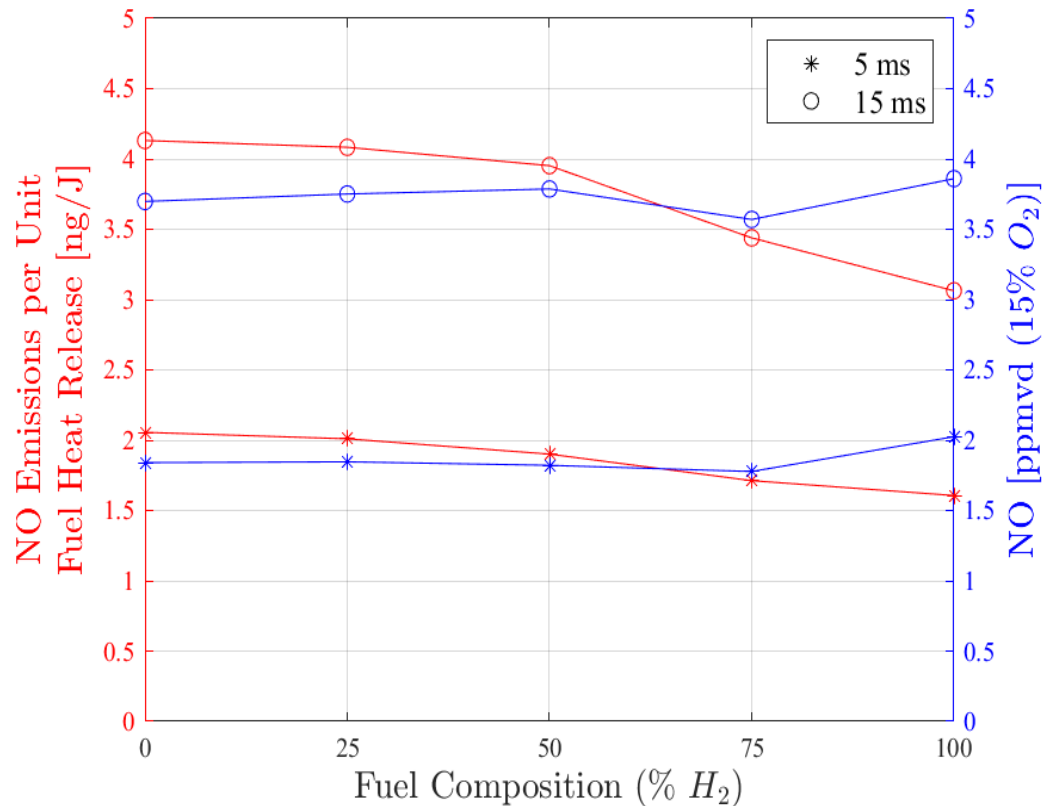
- Heating up air ($\text{N}_2 + \text{O}_2$) leads to NO production, even from 100% renewable fuels
- Hydrogen addition changes:
 - NO_x production pathways
 - Sensitivity to mixedness
 - Sensitivity to turbulence



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H₂/CH₄ Sensitivity in Premixed Limit

- Need for validated mechanisms



p= 20 bar, T_{in}=800K T_{ad}=1800K

NH₃ Work



Introduction

- Ammonia (NH_3) is being investigated as a possible carbon-free alternative energy source
 - Fuel-bound nitrogen introduces added NO_x penalty
- Staged combustion is a strategy employed to help reduce NO_x emission
 - Natural gas systems use lean primary stage with secondary fuel injection and short second stage that consumes all the fuel
 - RQL (Rich-Quench-Lean) used in systems with high turndown and fuel-bound nitrogen
 - Previous studies¹ have observed emissions as low as 50 ppm NO_x emissions, however, specific operating conditions and minimum achievable NO_x is unknown
 - Previous studies¹ also showed large amounts of H_2 produced in rich ammonia flames (over 3000 ppm)

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¹R.C. Rocha, M. Costa, X.-S. Bai, Combustion and Emission Characteristics of Ammonia under Conditions Relevant to Modern Gas Turbines, Combustion Science and Technology 193 (2021) 2514-2533.

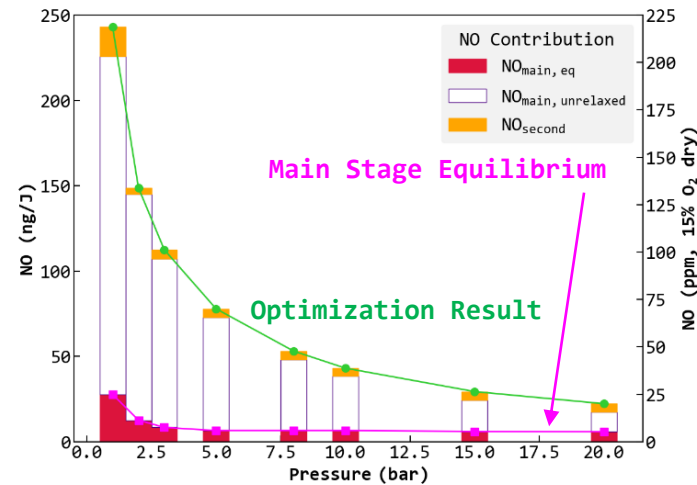
Background Question:

- A useful benchmark:
 - What is the theoretical minimum possible NO and N₂O emissions from ammonia combustion?
 - What do combustors optimized for ammonia look like?

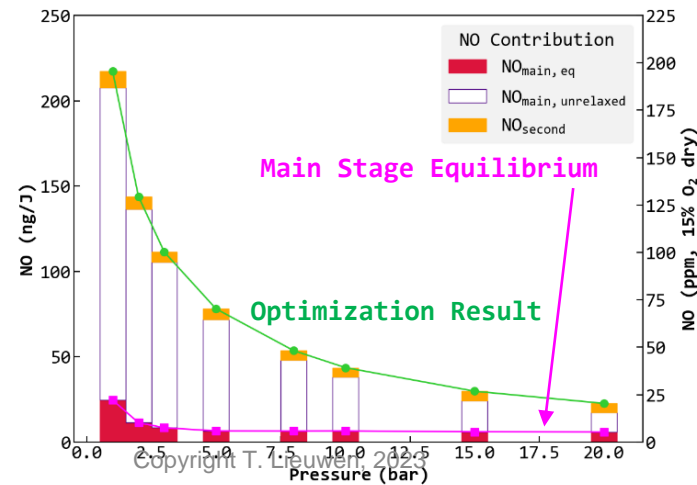
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Combustor Pressure Sensitivities

- High pressure allows main stage to approach equilibrium faster, decreasing $\text{NO}_{\text{main,unrelaxed}}$ and overall NO emission
 - As low as 25 ng/J (23 ppm) NO emission achievable
- Bigger discrepancy in NO emissions at lower pressures between temperature conditions



(a) $T_{\text{exit}} = 1750 \text{ K}$



(b) $T_{\text{exit}} = 1900 \text{ K}$

Minimum NO for varying combustor pressure at (a) $\Phi_{\text{global}} = 0.559$ (b) $\Phi_{\text{global}} = 0.672$ ($\tau_{\text{global}} = 20 \text{ ms}$)

Overview of US R&D Work

- Cycle innovations
 - Oxyfuel – Allam, etc.
 - Air breathing – Efficiency
 - Carbon capture
- Combustor:
 - Operability
 - Pollutant emissions, including optimized designs for ammonia
 - Fuel flexibility
 - Turndown
- Turbine
 - Increasing TIT, life

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