Hydrogen Use in Gas Turbines:

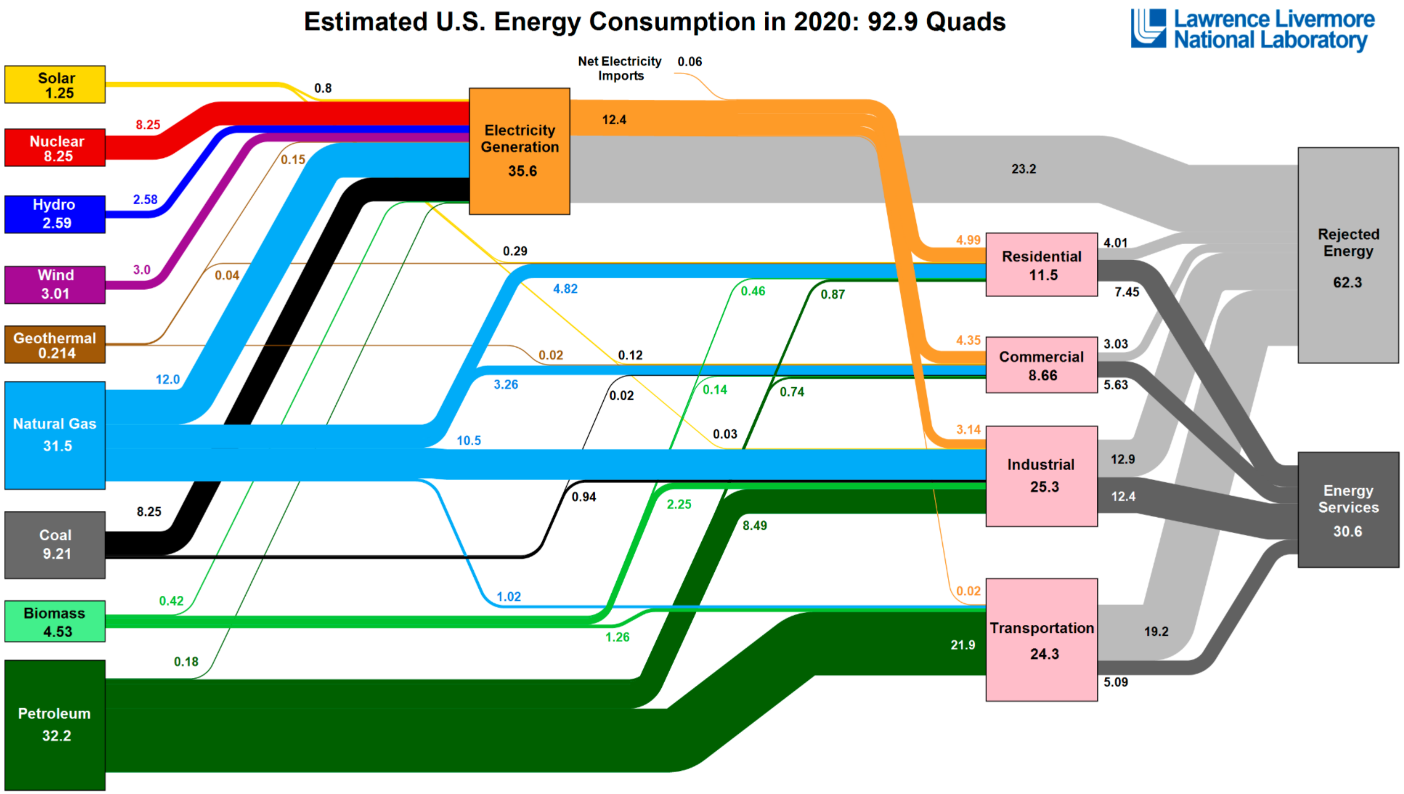
Operability, Emissions, Efficiency

Tim Lieuwen

Georgia Tech

Robin Ames

U.S. Energy System – Supply View



Source: LLNL March, 2021. Data is based on DOE/EIA MER (2020). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

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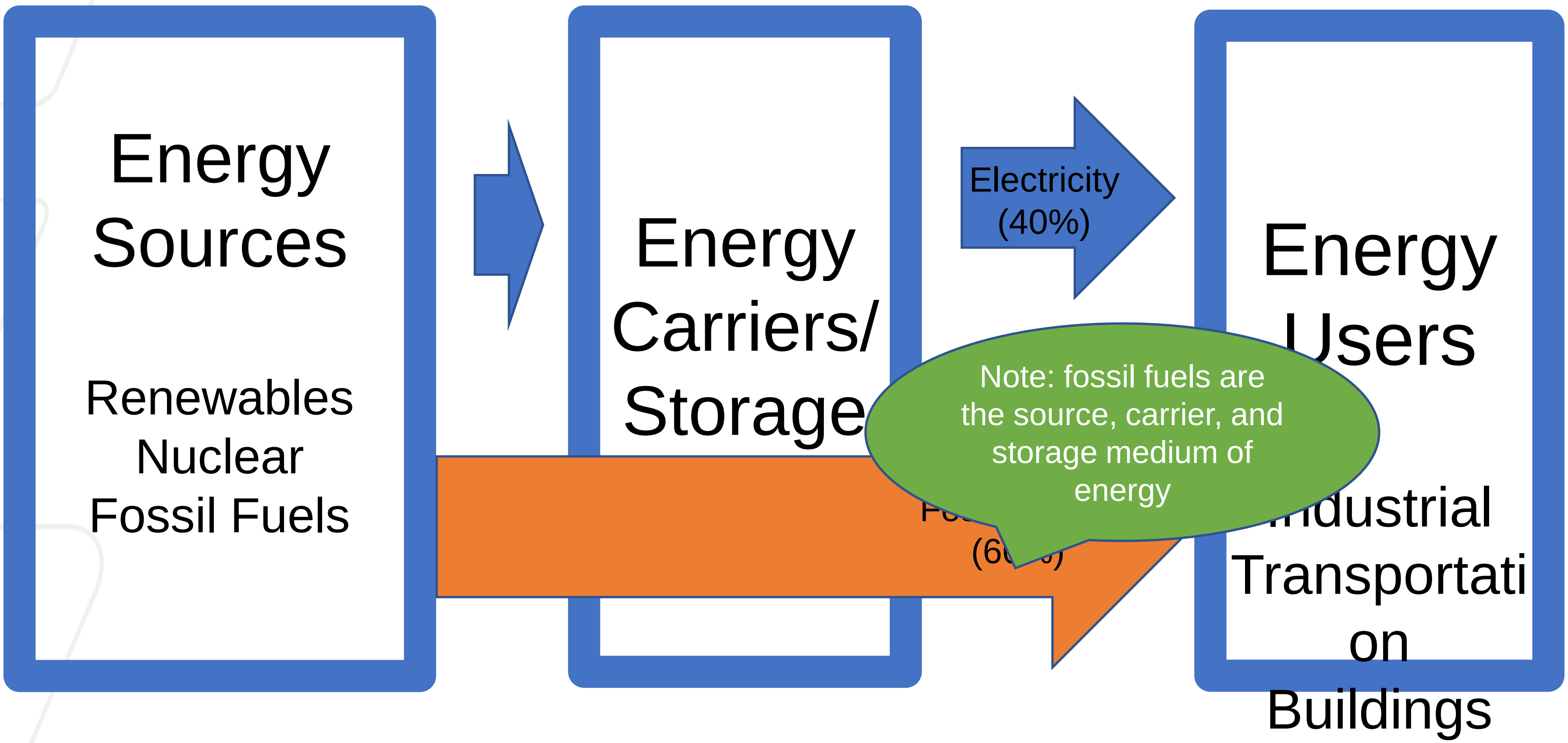
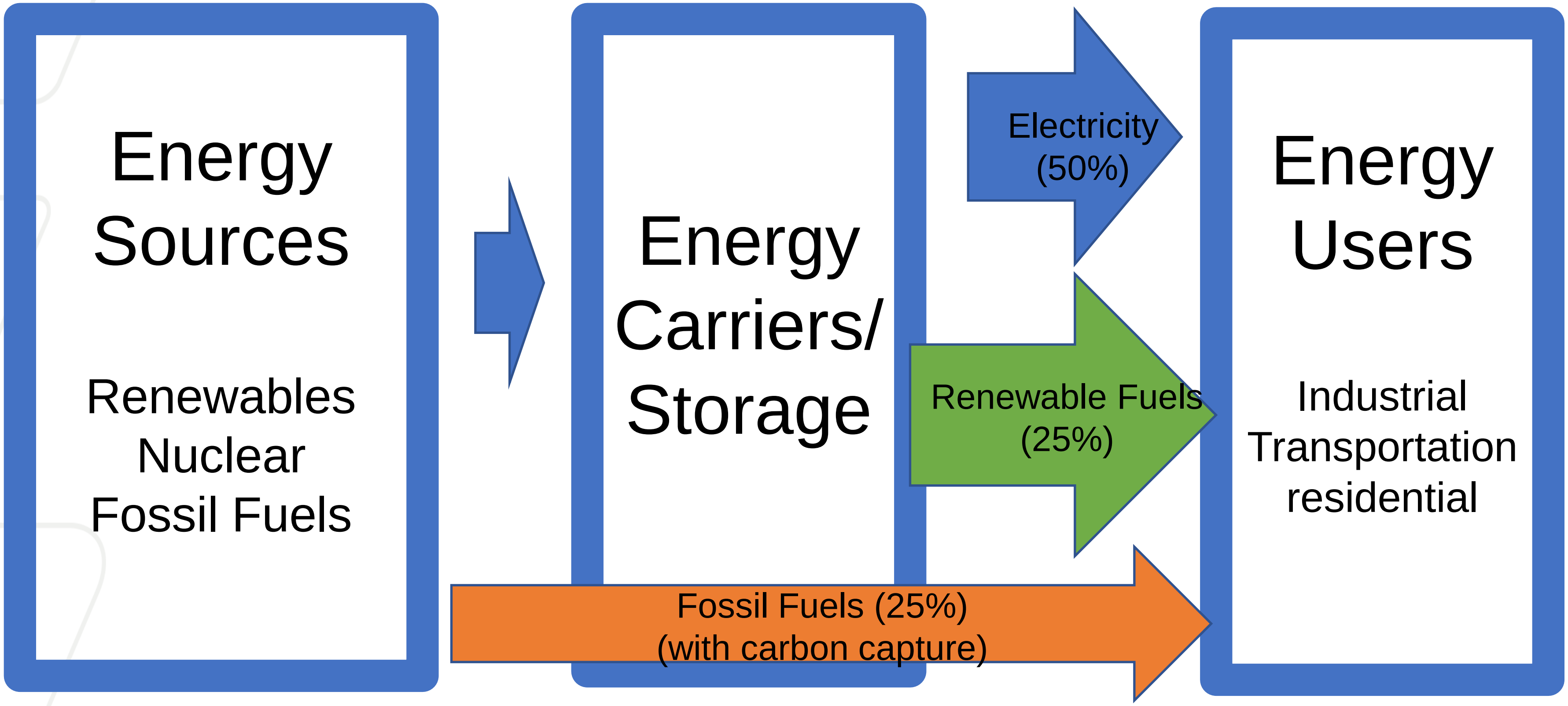
US Energy System



US Energy System – What will the net-zero CO_2 system look like?



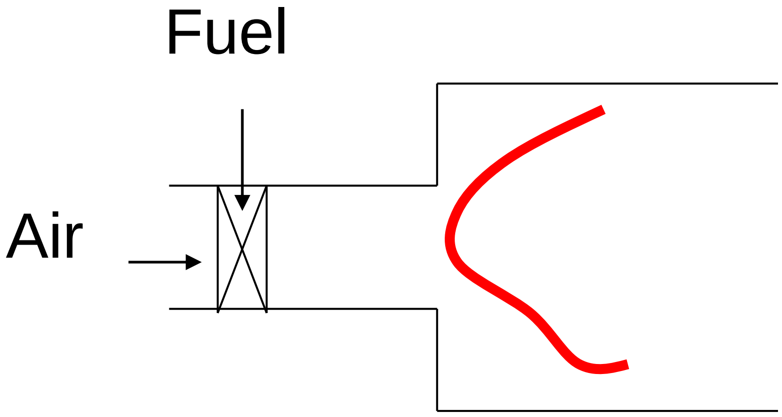
Source: Jesse Jenkins, Princeton University

H_2 Interactions with Gas Turbine Performance Metrics

- Cycle
  - Efficiency and power output

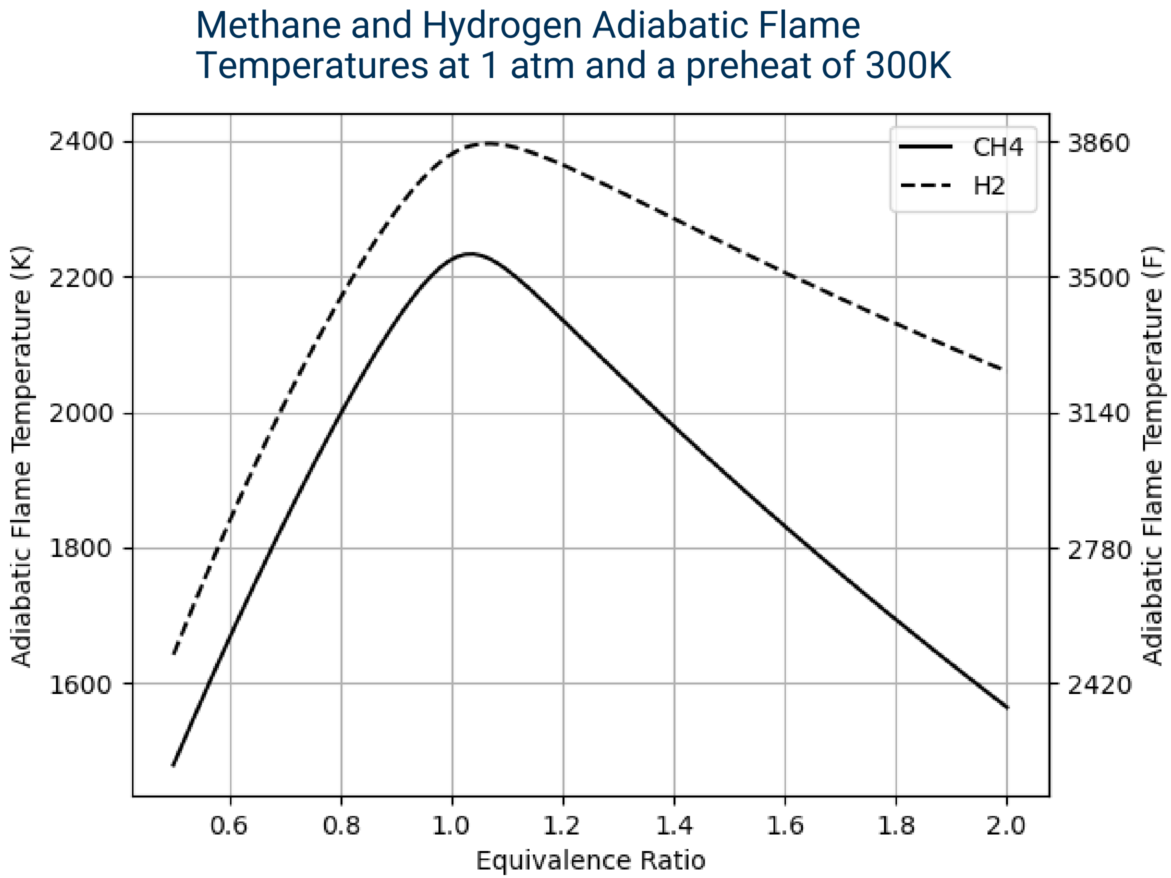
- Combustor:
  - Operability
  - Pollutant emissions
  - Fuel flexibility
  - Turndown

- Turbine
  - Heat transfer



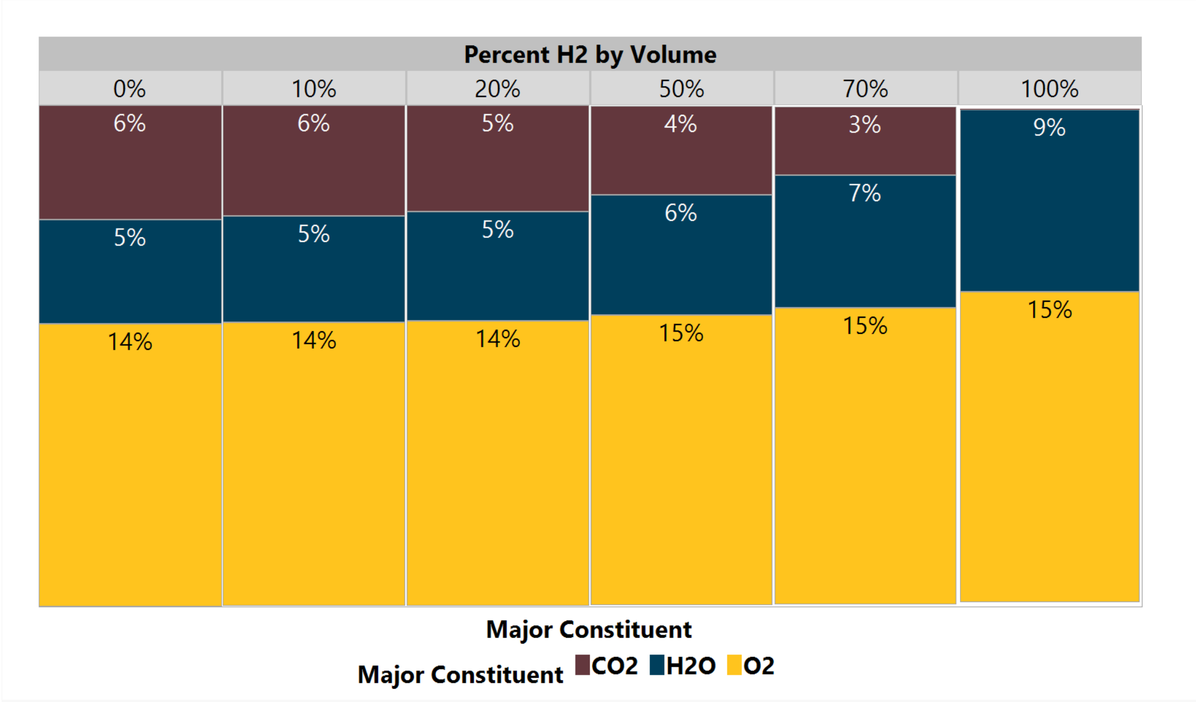
Flame Temperature

- Primarily depends upon fuel/air ratio (ϕ) and compressor discharge temperature
- Peaks near ϕ=1
  - H_2 can be much hotter!



Heating Value and Exhaust Products (courtesy of B. Noble, EPRI)

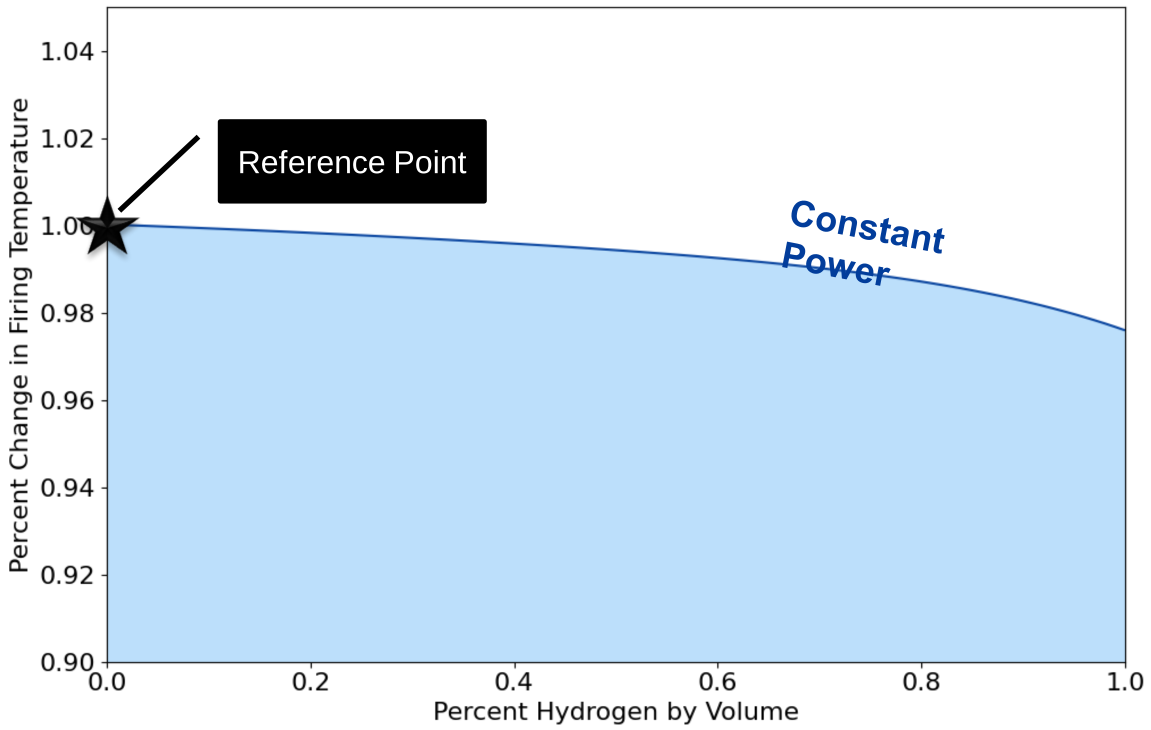
- H_2O carries **~2X** more 'energy' per pound than CO_2
  - This means you can add more energy (burned fuel) to raise air to the same temperature
- Any other species you measure in dried exhaust will be concentrated as you add H_2 (e.g., NOx)



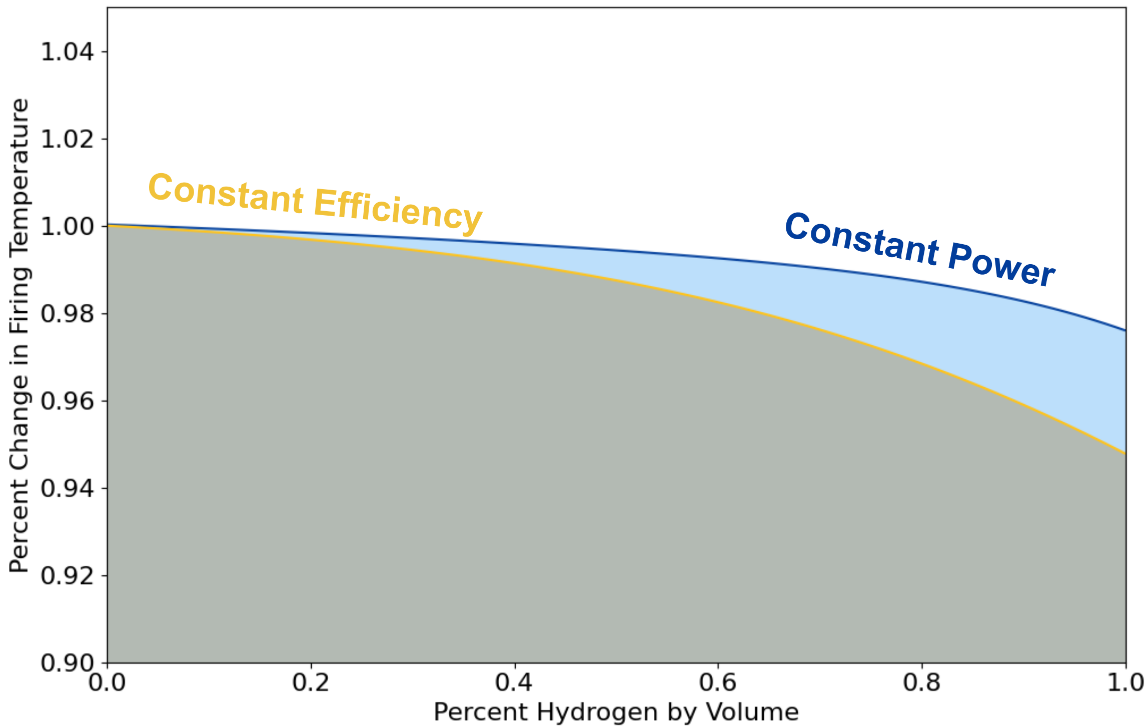
*Assumes constant firing temperature and inlet conditions

Cycle Effects

EFFICIENCY AND SPECIFIC POWER (COURTESY OF B. NOBLE, EPRI)



EFFICIENCY AND SPECIFIC POWER (COURTESY OF B. NOBLE, EPRI)



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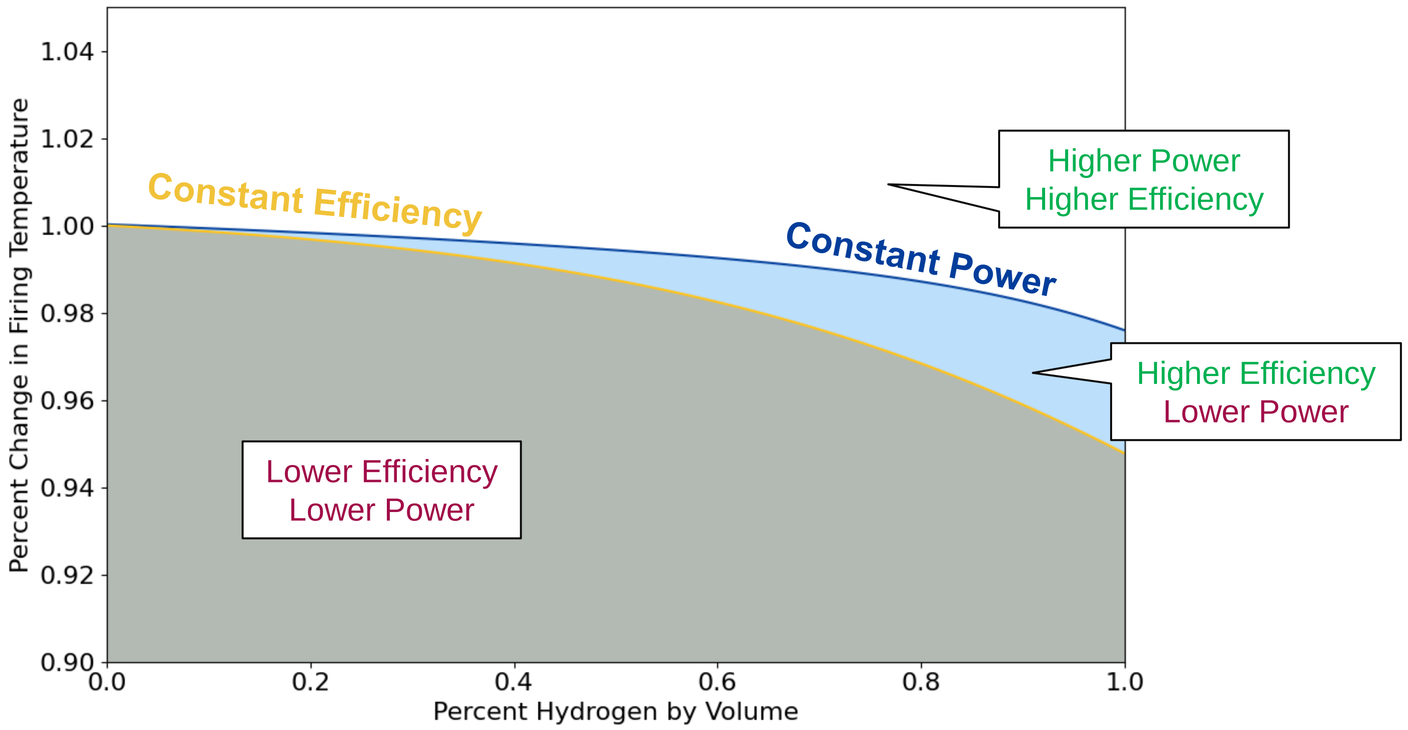

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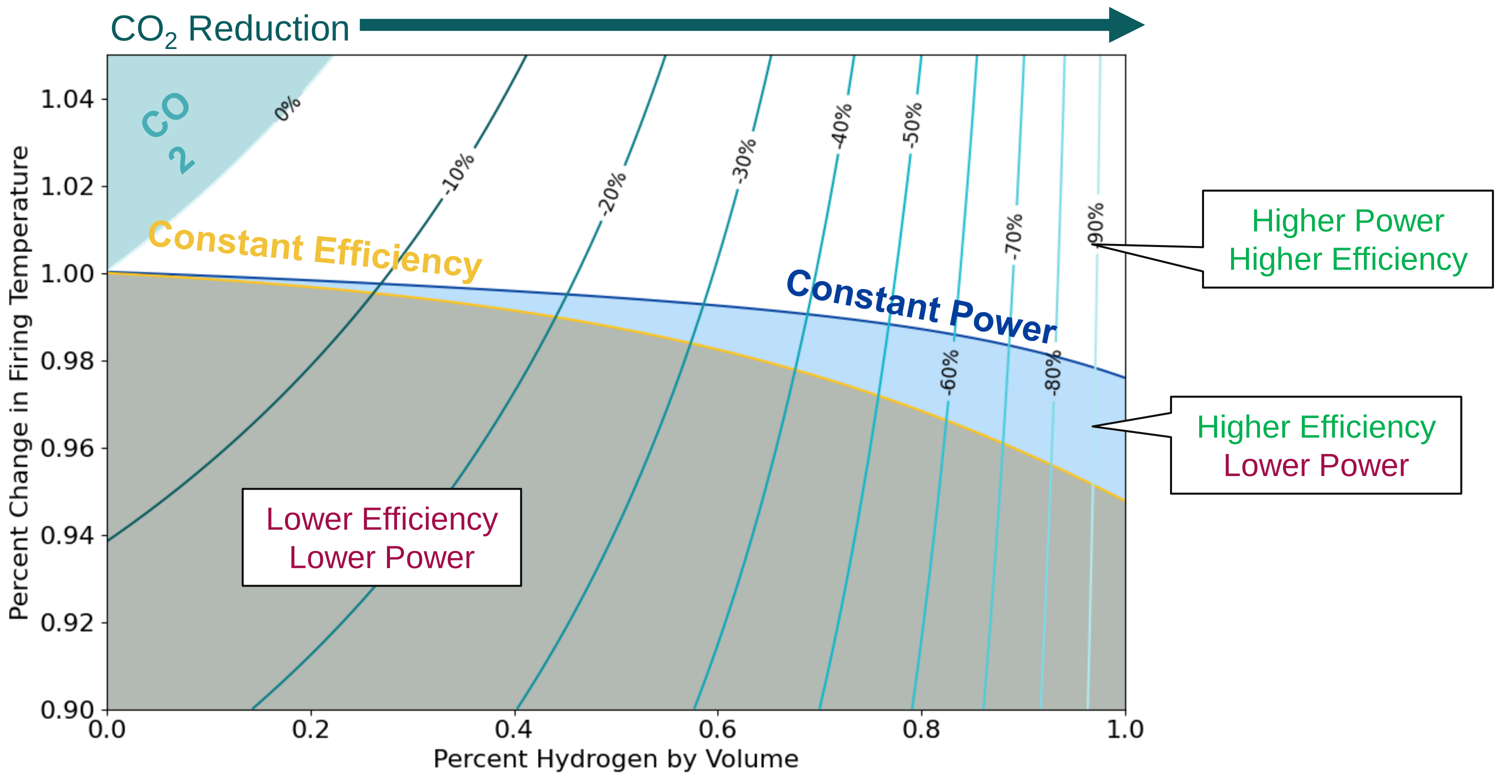

Combustor Effects

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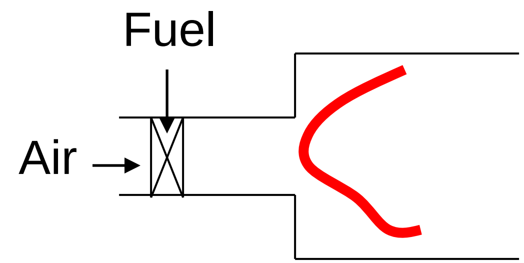
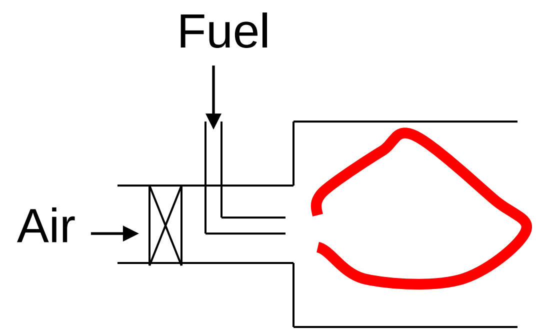
Premixed vs Non-Premixed Flames

- 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 ϕ=1
    - i.e., stoichiometry cannot be controlled
    - Hot flame, produces lots of NOx and soot (if burning a hydrocarbon)



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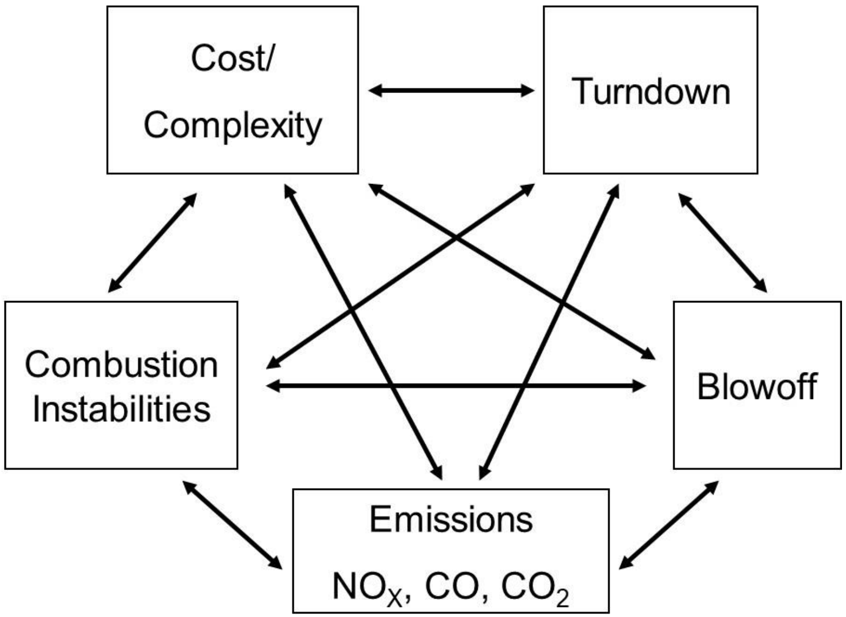
Combustor/Fuel Interactions

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



- Pollutant Emissions

Combustor/Fuel Interactions

- Operability:
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- Pollutant Emissions

Blowoff

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

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Industry Advisory
June 26, 2008

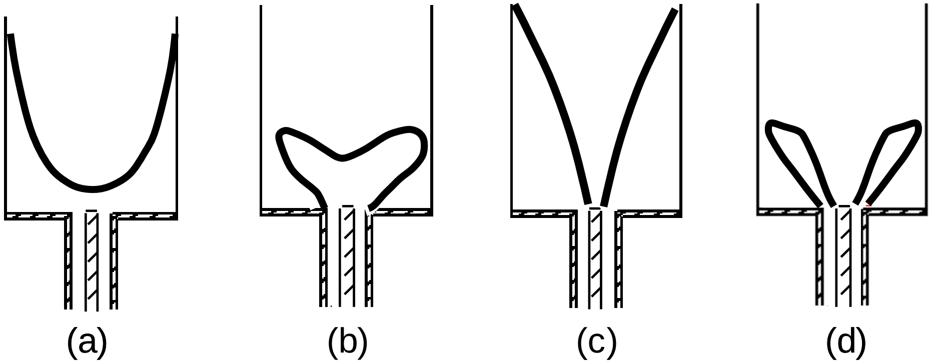
Background:

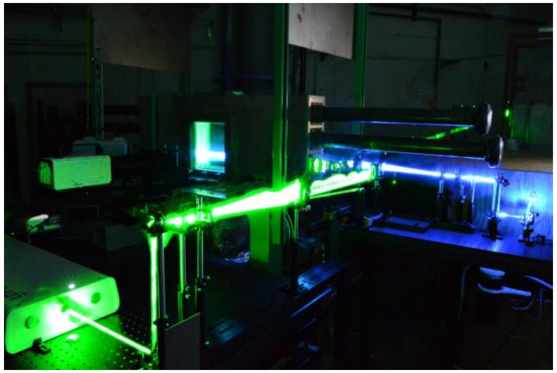
On Tuesday February 26th, 2008, the FRCC Bulk Power System experienced a system disturbance initiated by a138 kV transmission system fault that remained on the system for approximately 1.7 seconds. The fault and subsequent delayed clearing led to the loss of approximately 2,300 MW of load concentrated 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.

Flame Stabilization and Blowoff

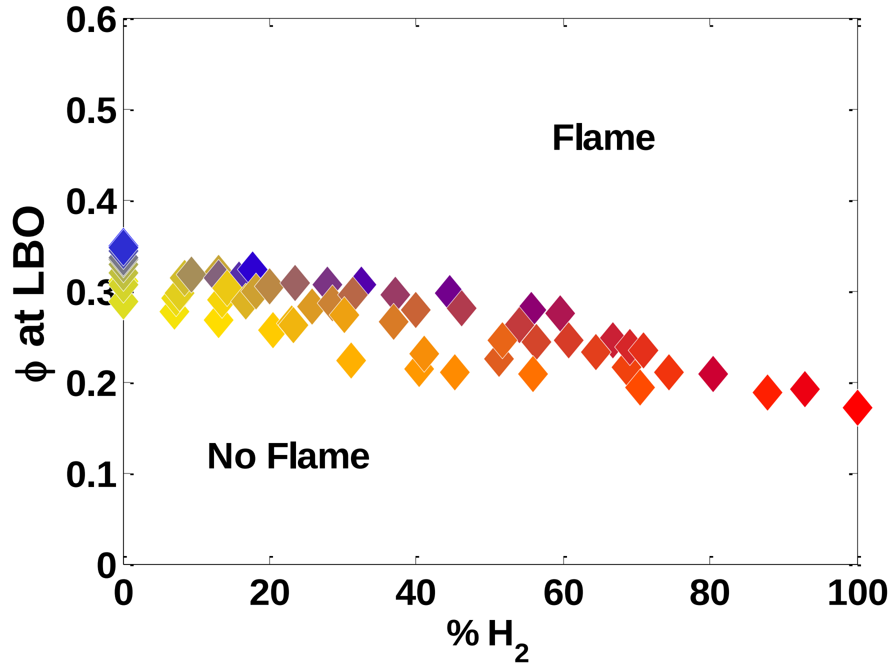
- Flame shapes controlled by local flame stabilization phenomenon
  - Controls combustion instability, heat loading, etc.





Blowoff

- H_2 addition significantly extends blowoff limits



Combustor/Fuel Interactions

- Operability:
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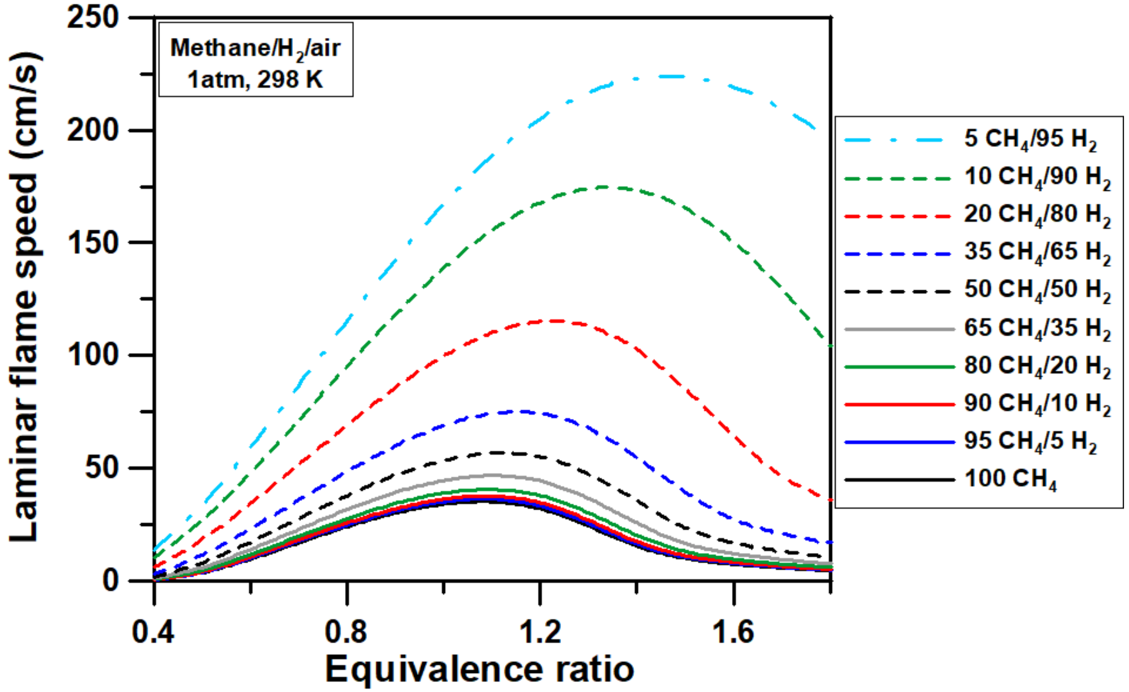
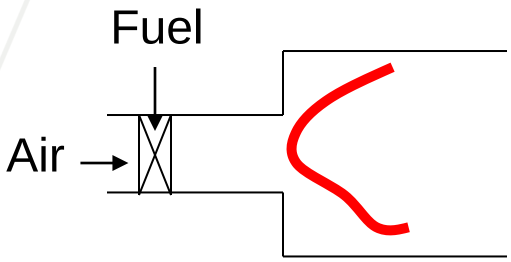
- Pollutant Emissions

Flashback

- Upstream propagation of a premixed flame into a region not designed for the flame to exist
- Occurs when flame speed exceeds the local flow velocity



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



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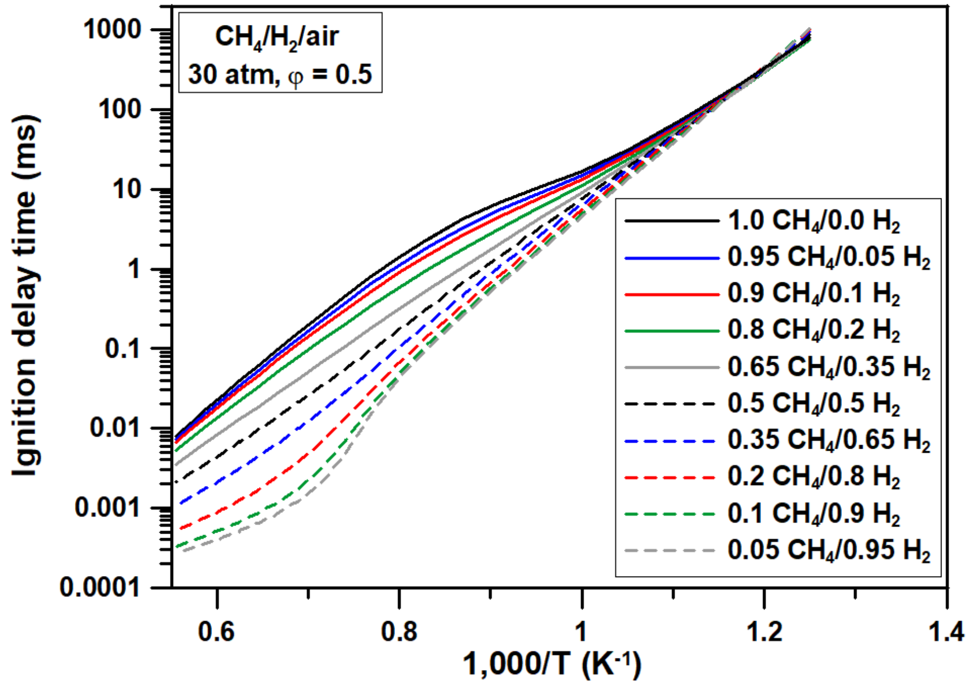
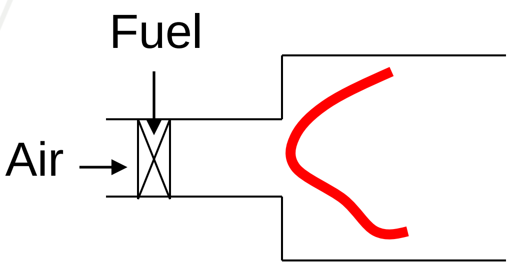
Autoignition

- 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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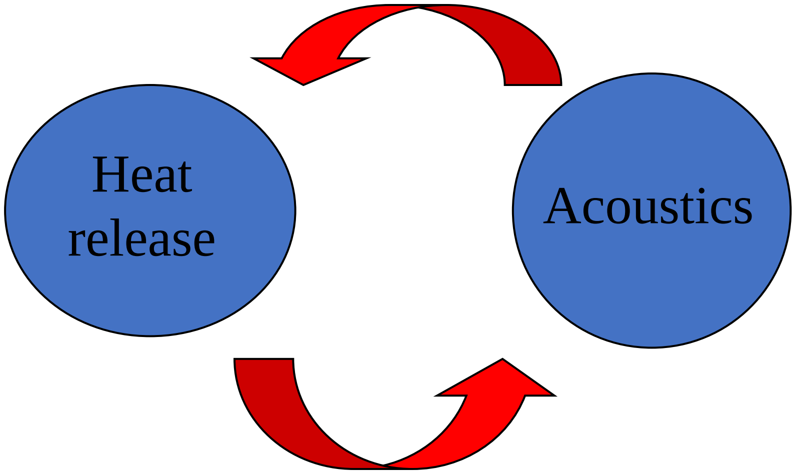
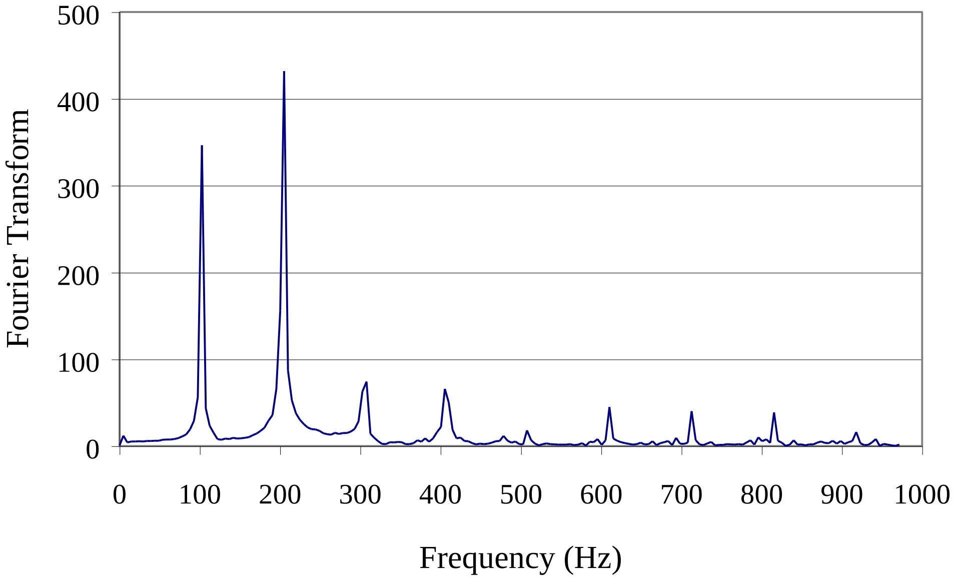
- Pollutant Emissions

Basic Feedback Cycle

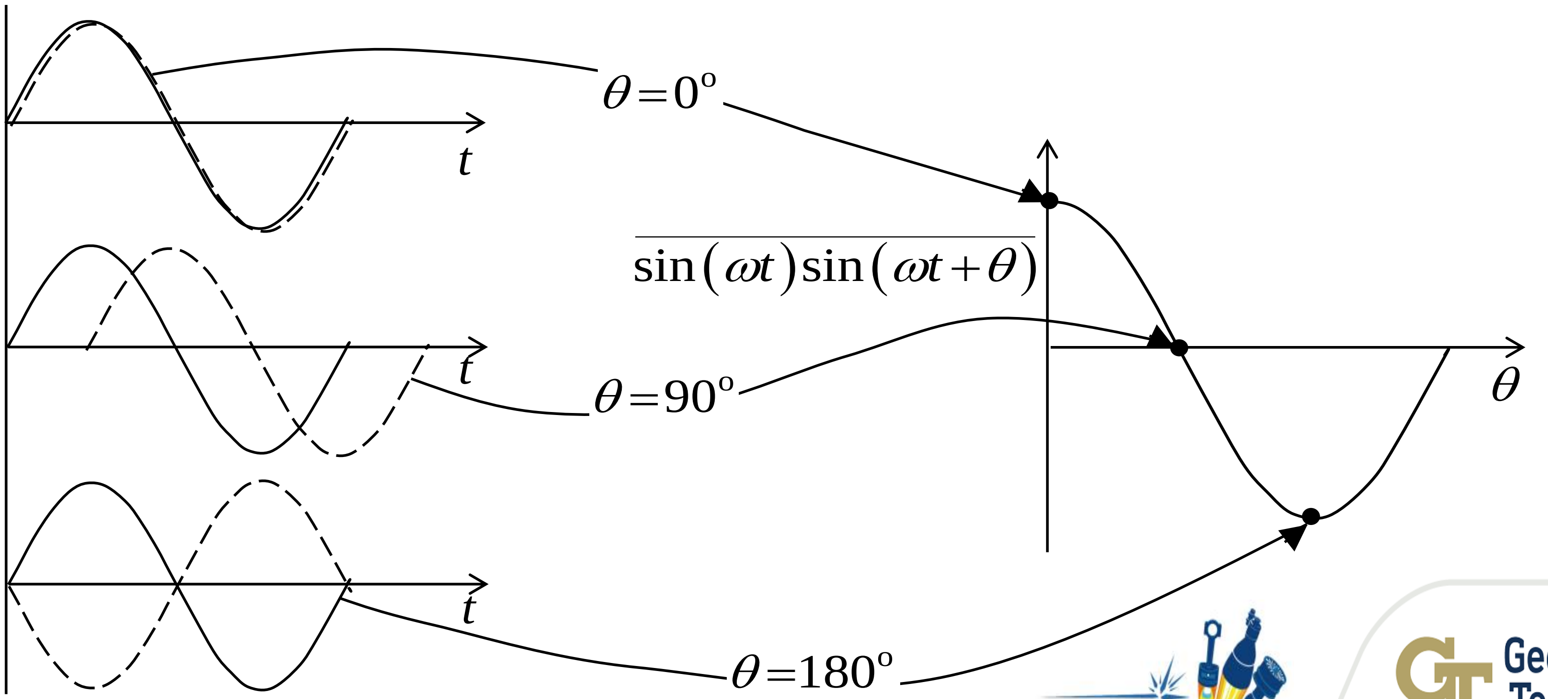
- Large amplitude acoustic oscillations driven by heat release oscillations
- Oscillations occur at specific frequencies, associated with resonant modes of combustor





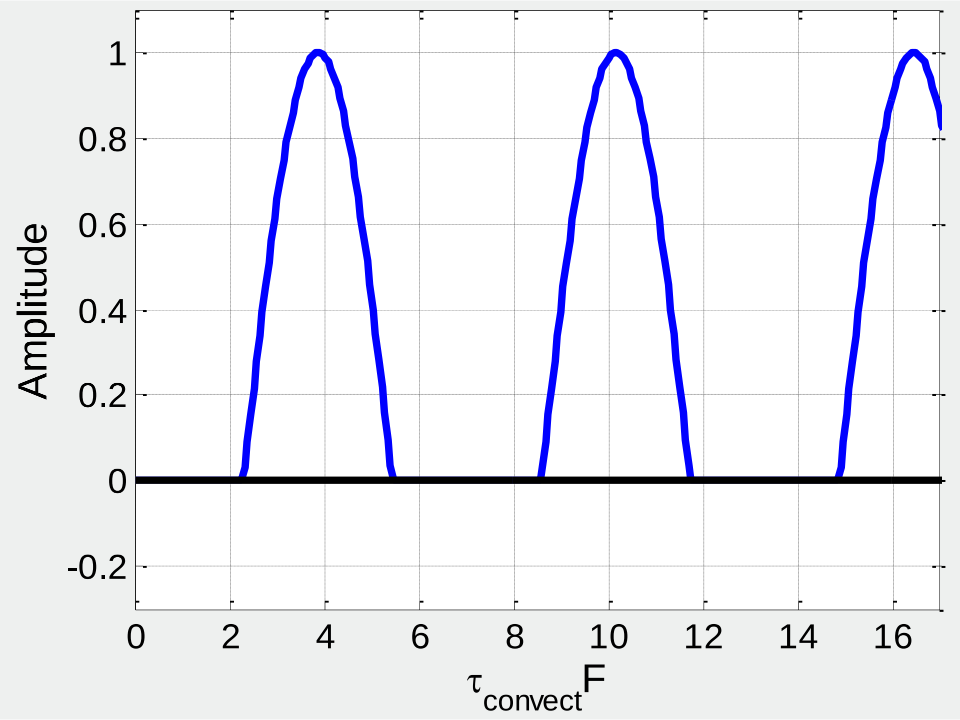
Rayleigh Criterion and Combustion Amplification of Sound

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

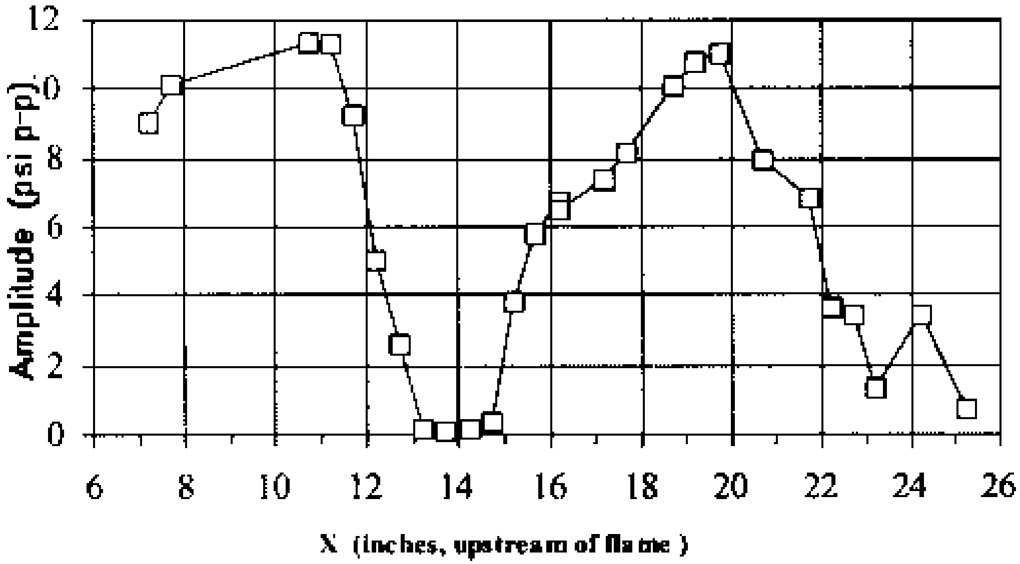


Combustion instabilities do not exhibit monotonic dependence upon fuel or operating conditions

- Instabilities can occur when:
  - $\cos(t_{convect}F)>0$
    - $t_{convect}$ = time required for mixture to convect from fuel injection point to flame
    - F= natural combustor frequency



Example: Fuel Injector Location



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

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

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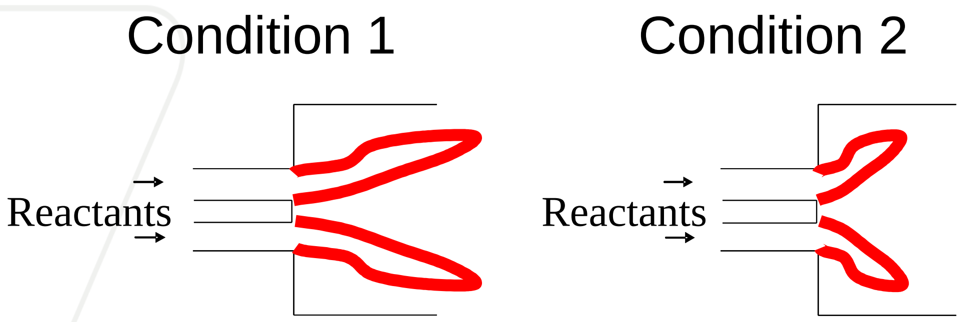
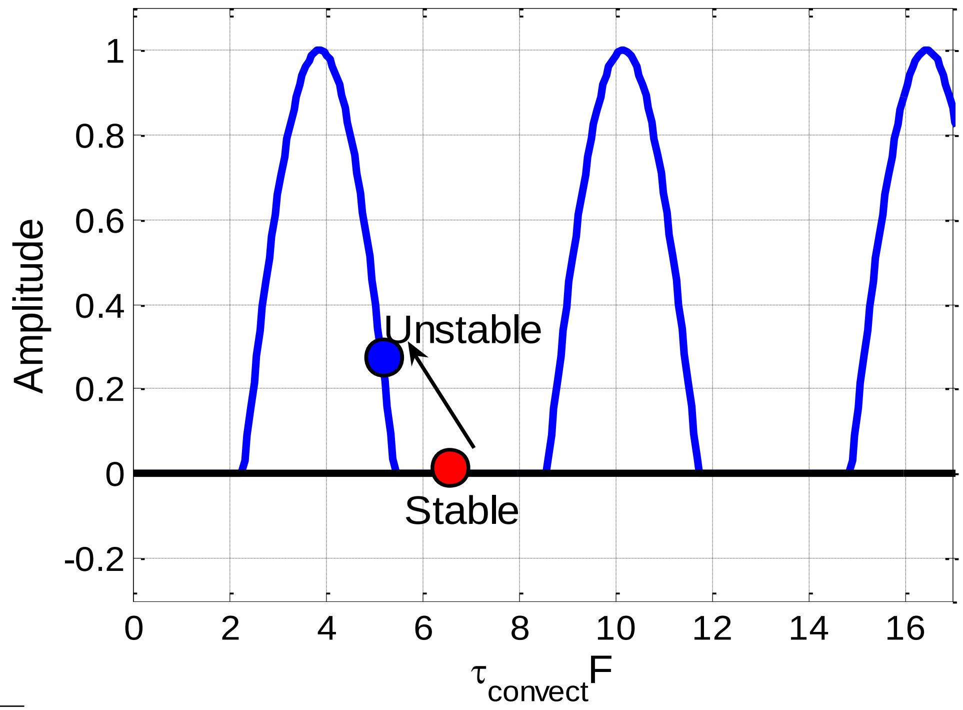
Example: H_2 addition to Natural Gas

- Key effect of H_2 on dynamics is through alteration of flame shape/location

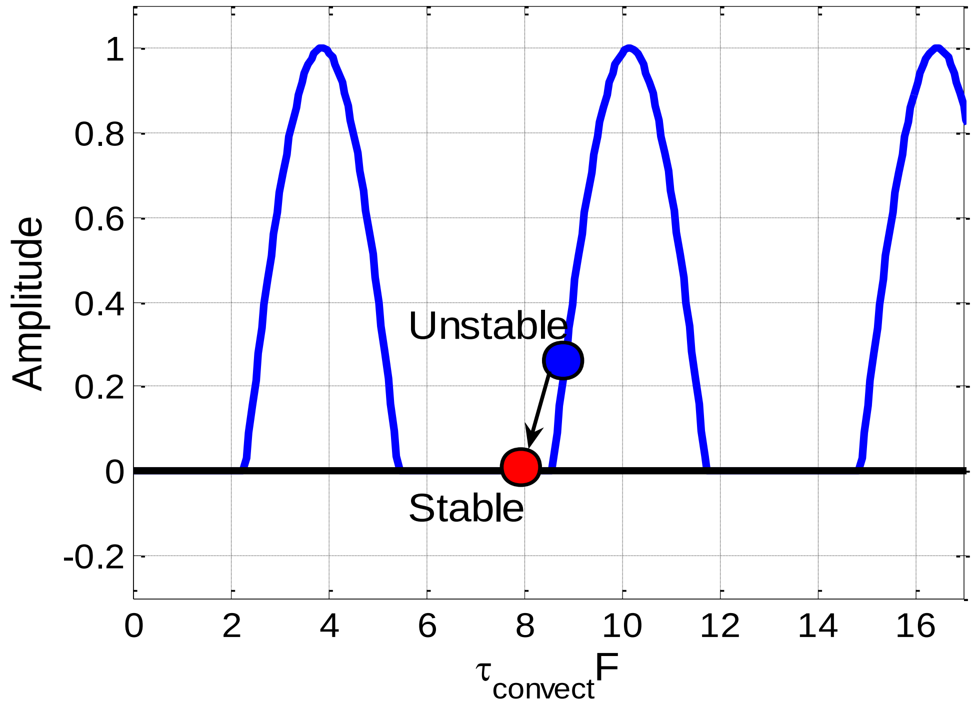


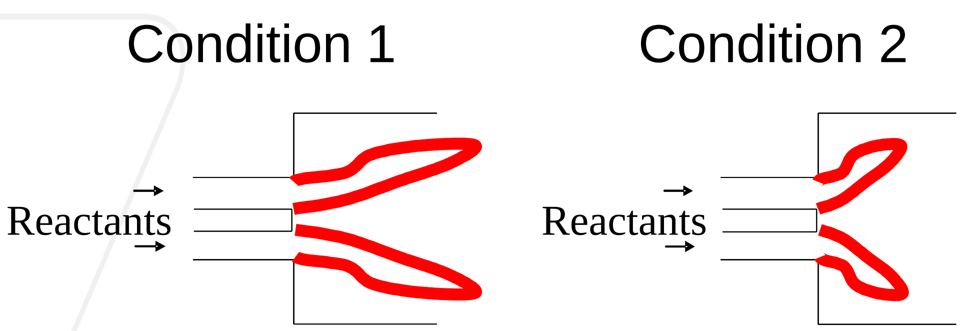


Example where dynamics made worse

Example: H_2 addition to Natural Gas

- Key effect of H_2 on dynamics is through alteration of flame shape/location
- Cannot make definitive comments on whether dynamics will be "better" or "worse" with H_2, except for near LBO dynamics





Example where dynamics made better

Combustor/Fuel Interactions

- Operability:
  - Blowout (“static stability”)
  - Flashback and autoignition
  - Combustion Instability (“dynamic stability”)

- Pollutant Emissions
  - NOx
  - CO
  - Soot/particulates
  - SOx

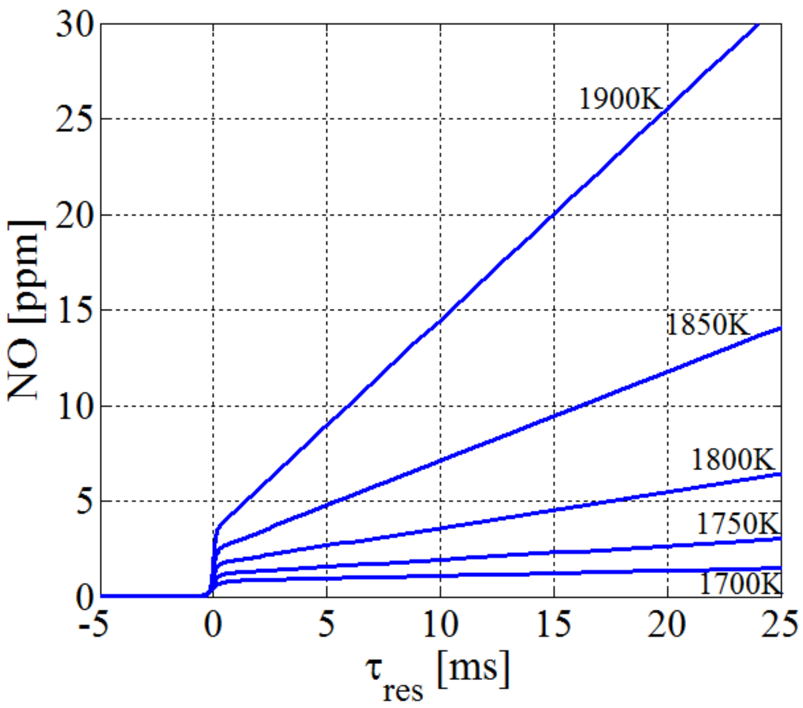
Combustor/Fuel Interactions

- Operability:
  - Blowout (“static stability”)
  - Flashback and autoignition
  - Combustion Instability (“dynamic stability”)

- Pollutant Emissions
  - NOx - a regulated pollutant; leads to smog and respiratory issues
  - ~~CO~~
  - ~~Soot/particulates~~
  - ~~SOx~~

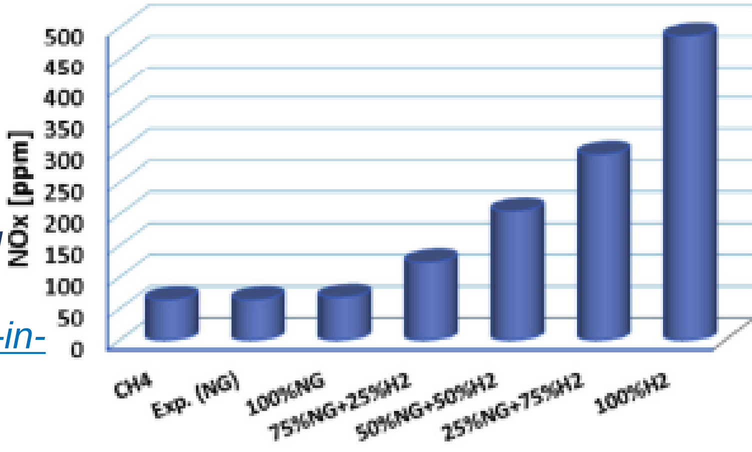
NOx Emissions – Basic Considerations

- Heating up air (N_2 +O_2) leads to NO production, even from 100% renewable fuels



BACKGROUND – DOES H_2 COMBUSTION EMIT MORE NO_X THAN CH_4?

- *"The bad news is that H_2 combustion can produce dangerously high levels of nitrogen oxide (NO_x). Two European studies have found that burning hydrogen-enriched natural gas in an industrial setting can lead to NO_x emissions up to **six times that of methane** (the most common element in natural gas mixes). There are numerous other studies in the scientific literature about the difficulties of controlling NO_x emissions from H_2 combustion in various industrial applications. "*
  https://www.renewableenergyworld.com/hydrogen/hydrogen-hype-in-the-air/#gref



HOWEVER,….

How to compare NO emissions with changing fuel composition?
Absolute vs. relative effects?
Results from "old-fashioned", high NOx devices; need for data in modern lean, premixed configurations

***Reference:** Mehmet Salih Cellek , Ali Pınarbası, "Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels"*

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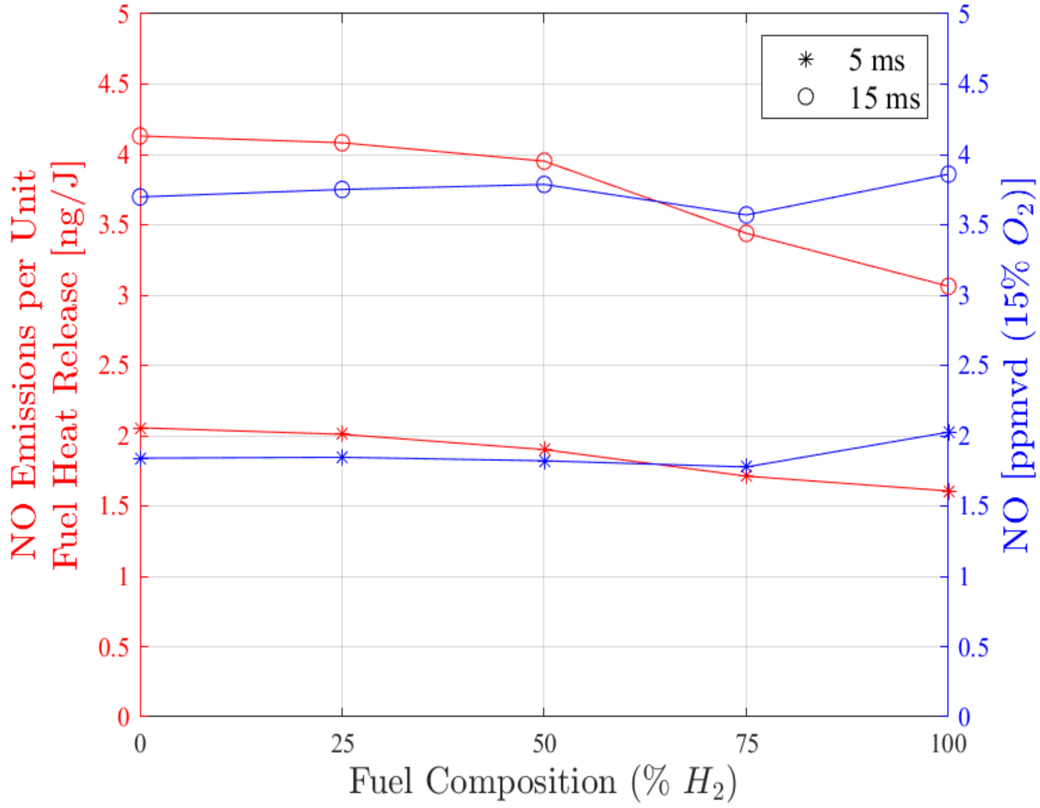
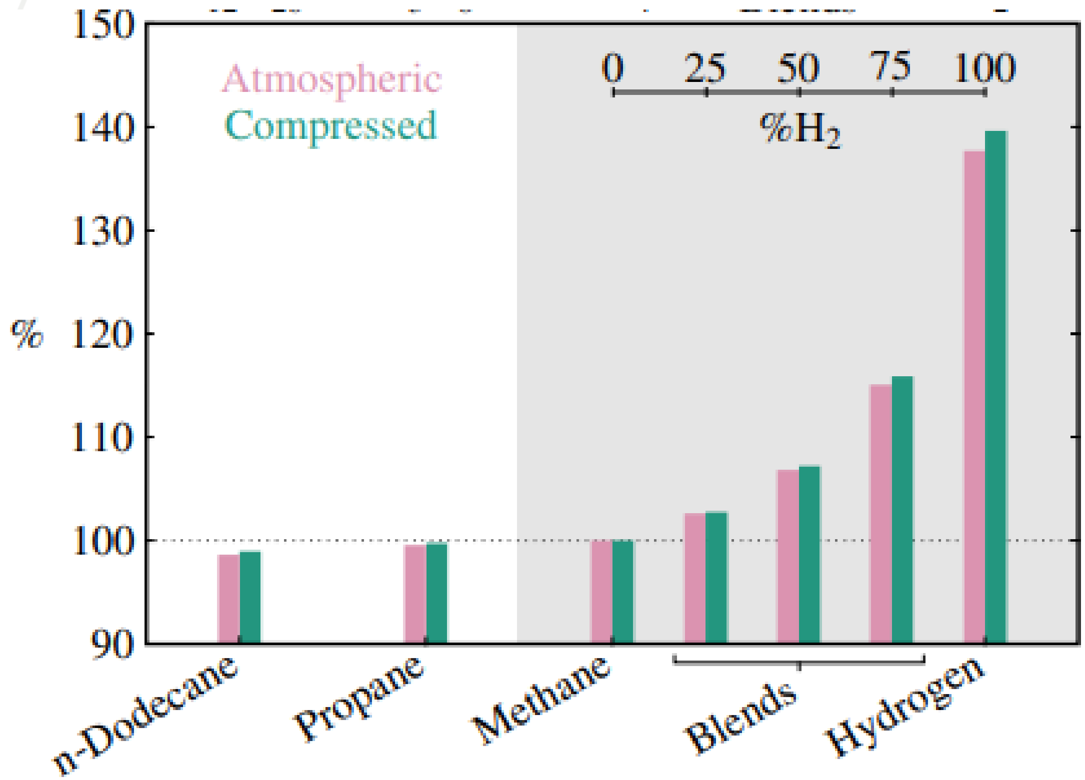
Weak H_2/CH_4 Sensitivity in Premixed Limit



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

NOx Emissions: Reporting and Quantification



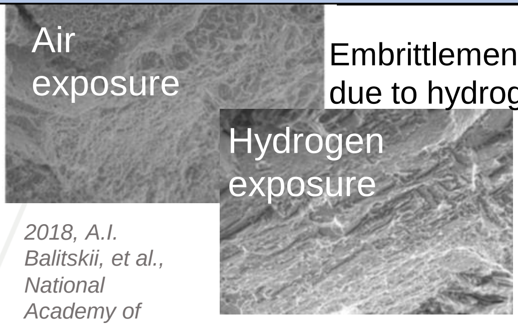
Relationship b/w ppmV@15%O2 and g NO/J is fuel dependent!!!!

Douglas C.M., Shaw S.L., Martz T.D., Steele R.C., Noble B.R., Emerson B.L., Lieuwen T.C, *Pollutant emissions reporting and performance considerations for hydrogen-hydrocarbon fuels in gas turbines*, ASME paper number #80971

Turbine Interactions

Using hydrogen as a fuel will have impacts on the turbine section (Slide Courtesy of K. Thole, Penn State)

Hydrogen/water effects on materials and coatings for the turbine components

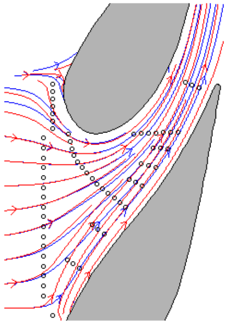


Embrittlement due to hydrogen

2018, A.I. Balitskii, et al., National Academy of Sciences of

TBC degradation due to water content

Impact to velocity triangles due to gas properties

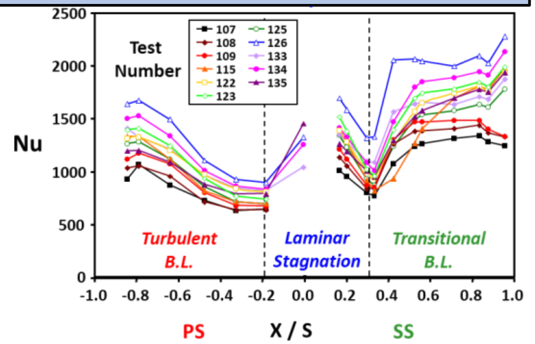


Changes in flow properties (density) impacts flowfield

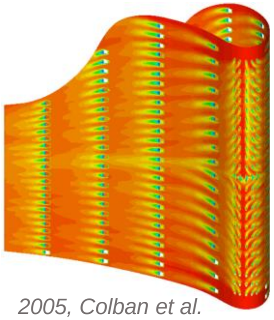
Combustor exit profiles for turbine inlet conditions

Blade heat transfer variation due to combustor exit profiles

2005, Barringer et al.



Increase of radiative loads to HPT 1st vane due to increased water vapor



2005, Colban et al.

Balance of radiation/convection may change

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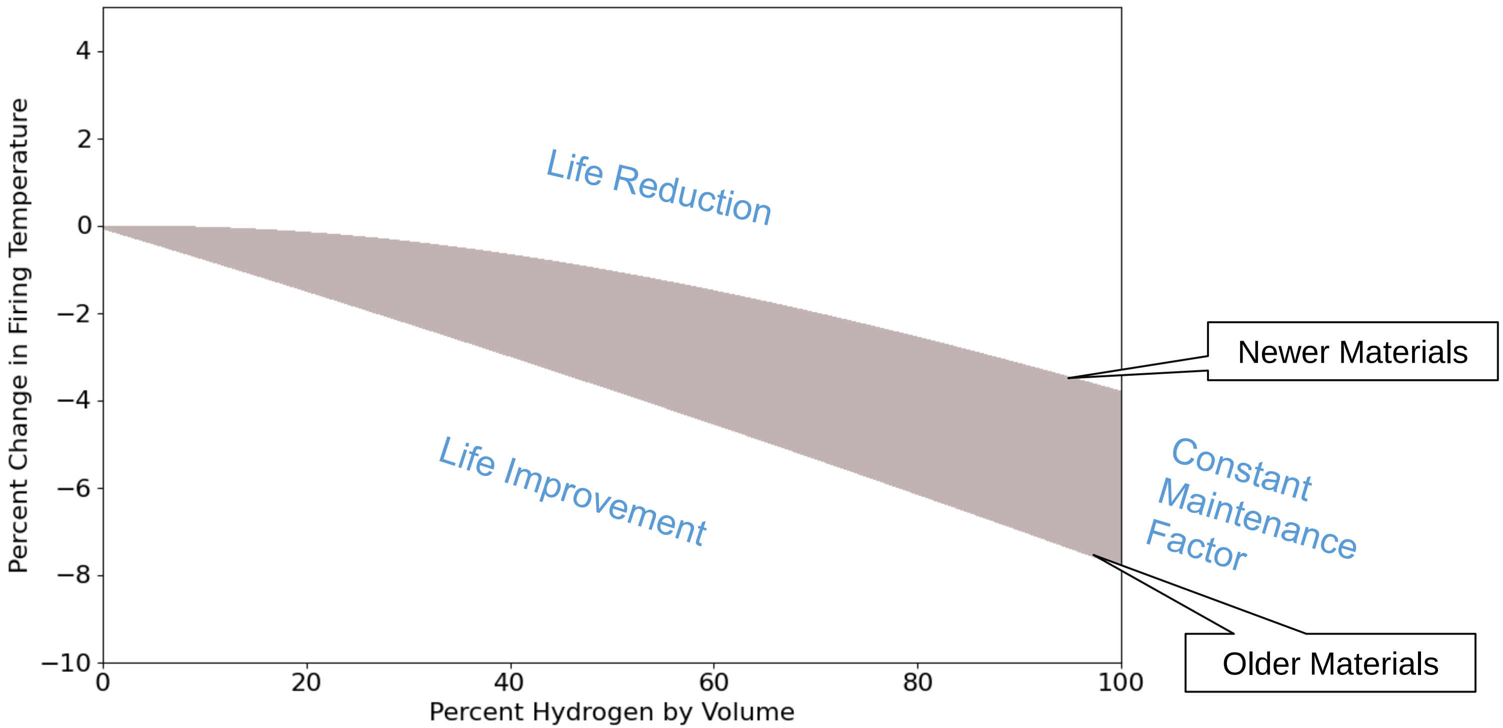
Maintenance Interval Impact (courtesy of B. Noble, EPRI)



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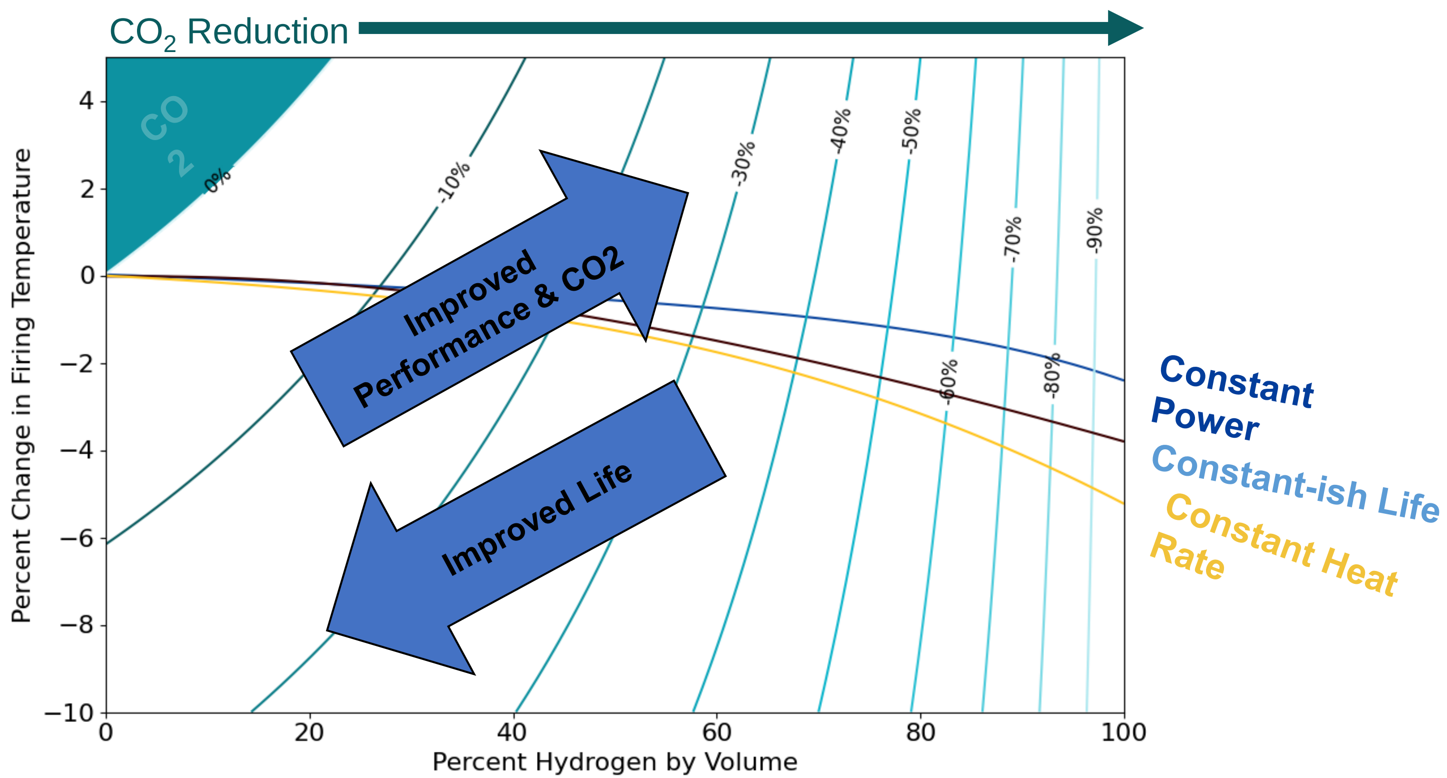
Efficiency, Specific Power, and Life (courtesy of B. Noble, EPRI)



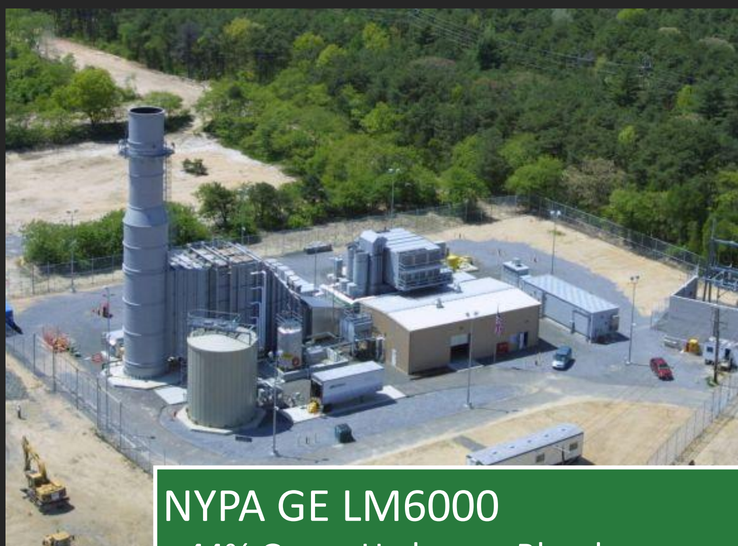
Closing Remarks

- Gas turbines have significant fuel flexibility

- Many gas turbine plants operating on hydrogen
  - Typically nonpremixed systems

- No conceptual, fundamental challenges for 100% H_2 operation
  - Key challenge – fuel flexibility with 0 and 100% H2

Its Happening!
Recent Aeroderivative and Frame Unit Demonstrations (courtesy of B. Noble, EPRI)



NYPA GE LM6000
- 44% Green Hydrogen Blend
- Standard Combustors/Water Injection
- Maintained NOx & CO reduction

Georgia Power M501G
- 20% Hydrogen Blend
- DLN Combustion System
- Maintained NOx
- Increased Turndown Capability