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The #H2IQ Hour

Today's Topic:

DOE Low NOx Targets and State-of-the-Art Technology for Hydrogen Fueled Gas Turbines

This presentation is part of the monthly H2IQ hour to highlight hydrogen and fuel cell research, development, and demonstration (RD&D) activities including projects funded by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE).

Housekeeping

This webinar is being recorded.

This webinar is being recorded and will be available on the H2IQ webinar archives.

Technical Issues:

- If you experience technical issues, **please check your audio settings under the "Audio" tab.**
- If you continue experiencing issues, direct message the host, Cassie Osvatics

Questions?

There will be a Q&A session at the end of the presentation.

To submit a question, please type it into the **Q&A box on the right-hand side of your screen next to the chat box/Chat**

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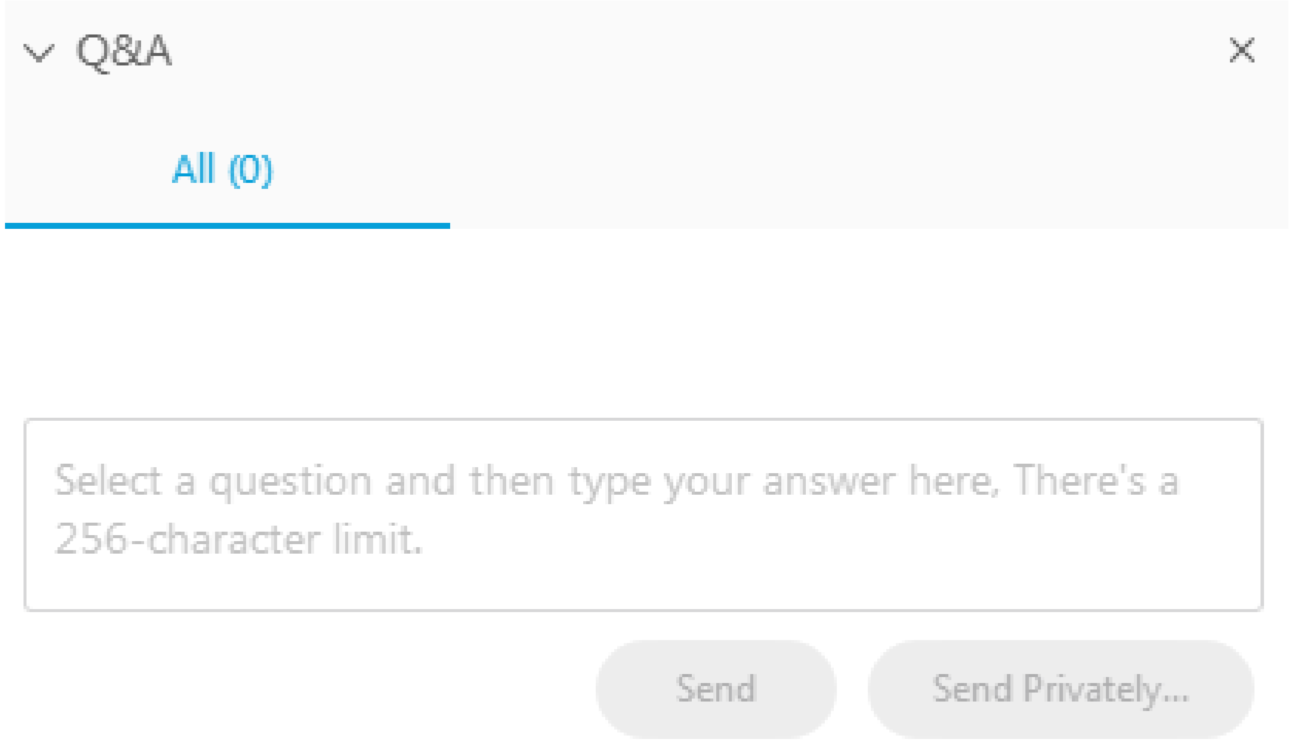
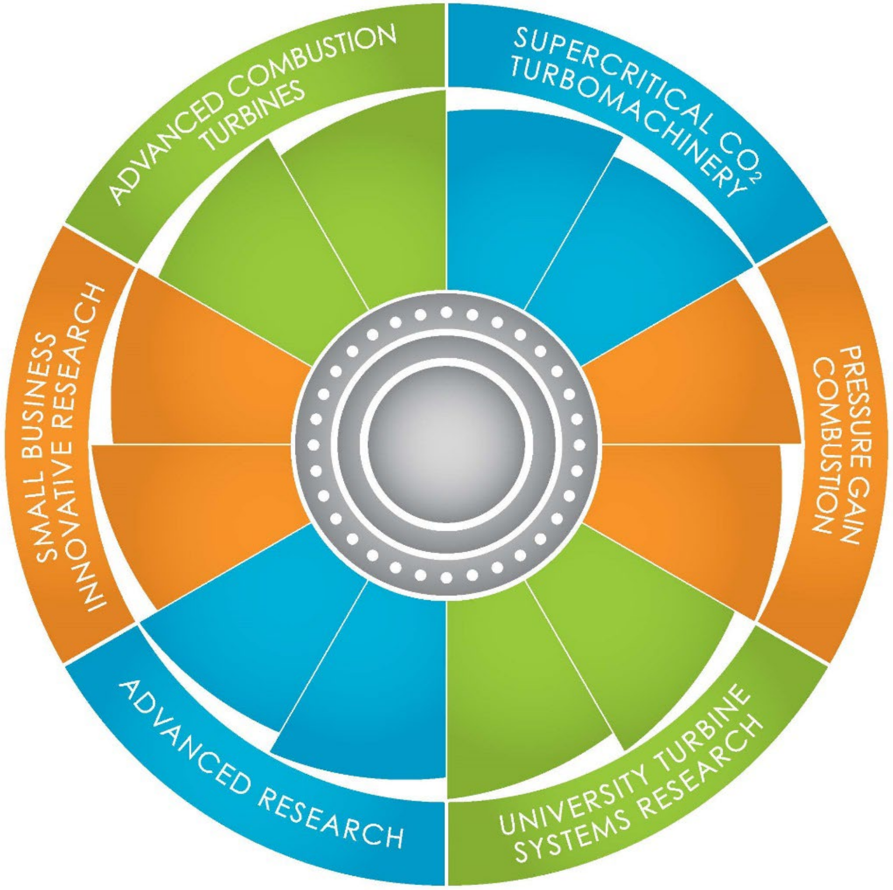
The #H2IQ Hour Q&A

Please type your questions into the **Q&A Box**



DOE Low NOx Targets and State-of-the-Art Technology for Hydrogen Fueled Gas Turbines

DOE Program Record - NOx Emissions from Gas Turbines Fueled with Hydrogen



H2IQ Webinar

DOE FECM Program Record - NOx Emissions from Gas Turbines Fueled with Hydrogen

Web Based Meeting

September 15, 2022

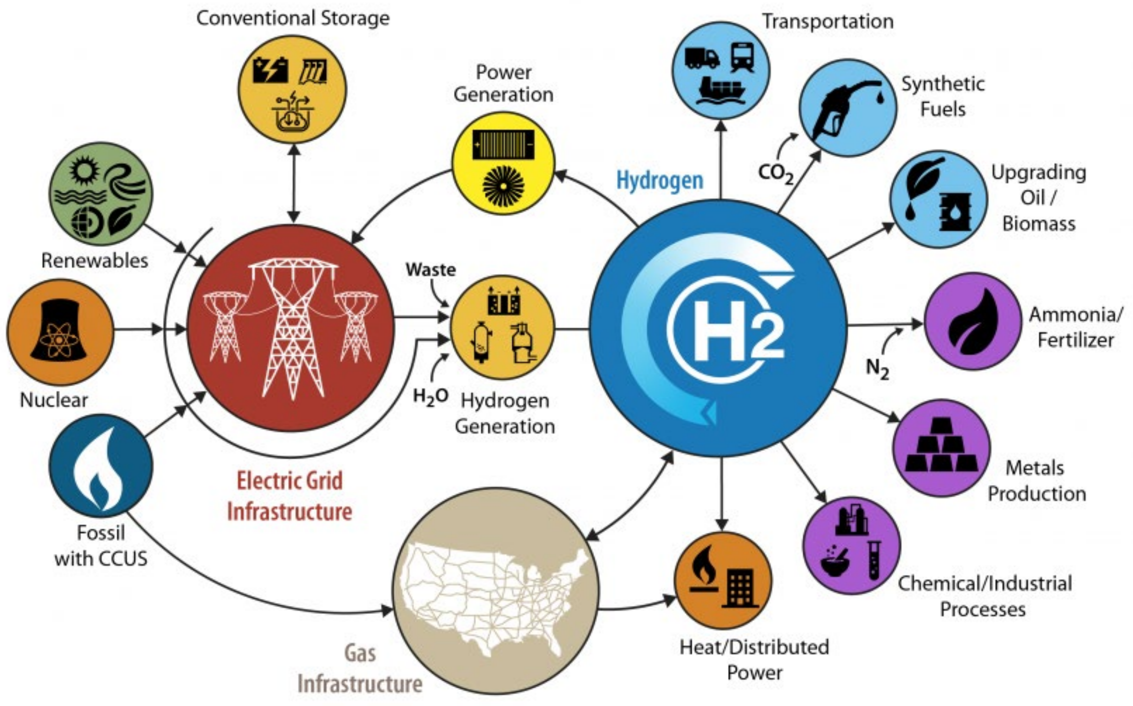
Time: 12:00 – 1 PM EST

H2IQ Webinar – Outline & Introduction

DOE Low NOx Targets and State-of-the-Art Technology for Hydrogen Fueled Gas Turbines

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Introduction**
- **DOE FECM Hydrogen & Carbon Management Program Advanced Turbines Program**
  - Why hydrogen fueled gas turbines
  - FECM Advanced Turbines (AT) Program
  - Program Record
- **DOE Low NOx Targets & H2 Fueled Gas Turbines**
  - Dr. Vince McDonell, UC Irvine; Director UCI Combustion Laboratory
  - Dr. Jeff Goldmeer, GE Gas Power; Emergent Technology Director – Decarbonization
  - Dr. Pete Strakey, NETL Advanced Combustion Group Leader
- **Q&A**



FECM = Fossil Energy and Carbon Management

Advanced Turbines (AT) Program Goals

Mission - Deliver low cost, clean and carbon free electric power

NATIONAL ENERGY TECHNOLOGY LABORATORY

DOE Mission

- Carbon free electricity by 2035
- Net-zero emissions by 2050
- Create new clean energy jobs
- Revitalize communities
- Advance environmental justice

AT Program Goals

- **RD&D of gas turbines fueled with no-carbon fuels**
  - H2, H2 & NG blends, NH3 etc.
  - Low NOx and high performance
- **Pursue advanced efficiency**
  - Simple and combined cycle
  - RDE
- **Optimization for CCS**

CMC synergies with FECM Advanced Materials Program

Why Hydrogen Fueled Gas Turbines

Deliver low cost, clean and carbon free electric power

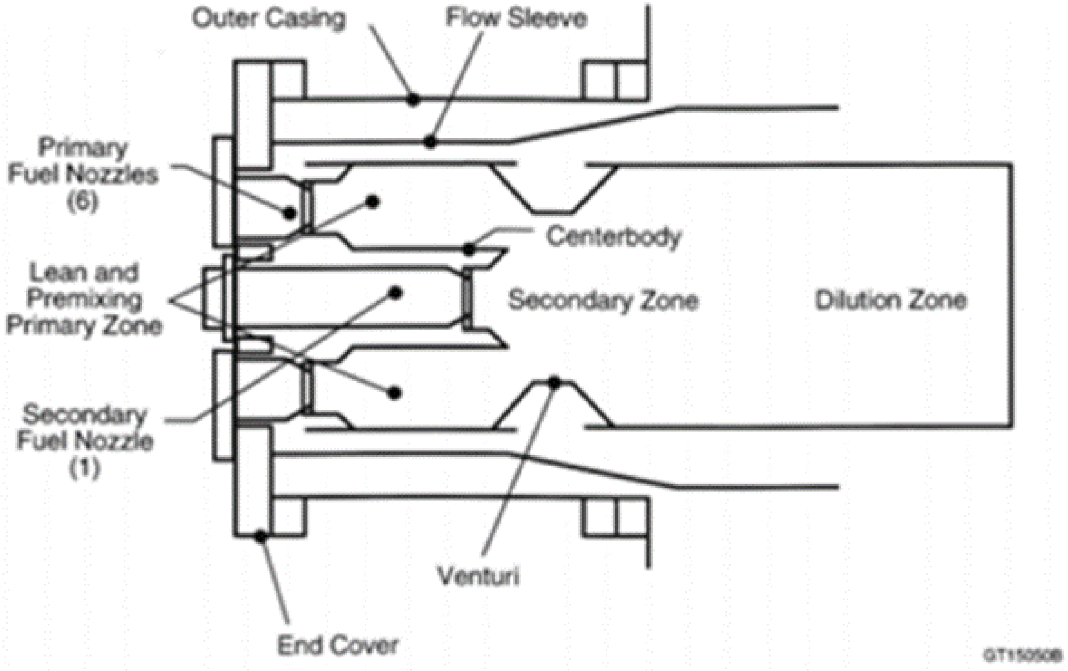
NATIONAL ENERGY TECHNOLOGY LABORATORY

- Carbon-free
- H_2 fuel blending
- Dispatchable
- Load following
- Exiting infrastructure
- Technology demonstrations

Fundamentals of Hydrogen Combustion

Hydrogen is unique compared to natural gas

- High flame temperature (2045ºC in air)
- High flame speed (3 m/s)
- NO_x formation routes
- Low mass density (MW = 2g/mol)
- Low volumetric energy density (10,050 kJ/m3 H_2 vs. 32,560 kJ/m3 CH_4)
- Combustion instabilities
  - thermoacoustic issues



Nominal Combustor Module

Gas Turbine NOx Requirements

NOx emission limits by turbine class, application, fuel and location (not shown)

- **Average actual NO_x ratings:**
  - B-to-F-Class: 5-9 ppm (older models up to 25 ppm)
  - H-Class: 9-15 ppm
  - Aeroderivative: 9-25 ppm
- **Smaller turbines generally have higher NO_x ratings**
- **NSPS for NG do not apply to Hydrogen ("other fuel")**

Current New Source Performance Standards (NSPS) (EPA)

EPA Category (Heat Input at baseload rating [HHV])	Market	Fuel	NO_x Limit @15% O_2 (based on gross energy output)
≤ 15 MW (50 MMBtu/hr.)	Power Generation	Natural Gas	42 ppm or 290 ng/J (2.3 lb./MW-hr.)
		Other Fuels	96 ppm or 710 ng/J (5.6 lb./MW-hr.)
	Mechanical Drive	Natural Gas	100 ppm or 690 ng/J (5.5 lb./MW-hr.)
		Other Fuels	150 ppm or 1100 ng/J (8.7 lb./MW-hr.)
15-250 MW (50-850 MMBtu/hr.)	Both	Natural Gas	25 ppm or 150 ng/J (1.2 lb./MW-hr.)
		Other Fuels	74 ppm or 460 ng/J (3.6 lb./MW-hr.)
≥ 250 MW (850 MMBtu.hr.)	Both	Natural Gas	15 ppm or 54 ng/J (0.43 lb./MW-hr.)
		Other Fuels	42 ppm or 160 ng/J (1.3 lb./MW-hr.)

Keeping Cost of Electricity (COE) Low

Hydrogen Turbines of the Future

- **Hydrogen's higher flame temperature can allow for higher pressure ratios, higher efficiency and lower COE**
- **Modifications necessary to optimize hydrogen combustors for low NOx**
- **DOE's goal is to achieve 100% H_2 utilization without sacrificing turbine performance or COE**

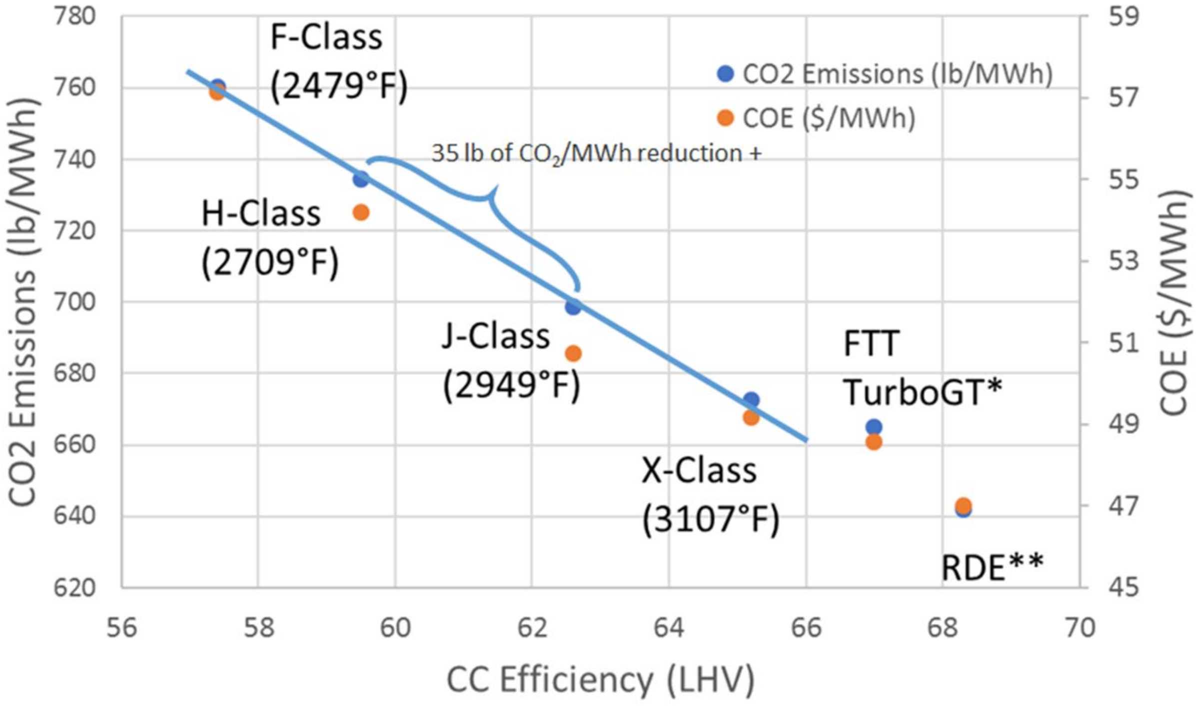


Figure is for natural gas fueled machines and illustrative of the impact of efficiency and firing temperature on efficiency and COE

Recent UTSR Advanced Turbine Awards

FY 21 UTSR Awards ($6.2 M)

- Hydrogen Combustion **Fundamentals** for Gas Turbines
  - Georgia Tech Research Corporation
  - The University of Central Florida
  - San Diego State University
- Hydrogen Combustion **Applications** for Gas Turbines
  - Purdue University
  - The Ohio State University
  - University of California, Irvine
- Hydrogen-Air **Rotating Detonation Engines (RDE)**
  - The University of Alabama
  - Purdue University

What will be done

- Explore chemical kinetics
- Investigate NOx & flame strain rate
- Investigate ignition delay times
- Measure flame speed
- Evaluate existing fuel injectors
- Flame structure and combustion dynamics for H2 & NH3 fuels
- Assess RDE combustion modes
- Develop design rules for micromixer injectors
- Develop CFD design tools

UTSR = University Turbine Systems Research

Recent Industry Advanced Turbine Awards

FY 22 Industry Awards ($28 M)

- **General Electric Company** – Combustors for H2 F-Class Retrofit ($6M / $12M)
- **Raytheon Technologies** – H2 Burner for FT4000 Aero Engine ($4.5M / $5.625M)
- **Solar Turbines** - GT Comb System for H2 & NG Blends ($4.5M / $5.625M)
- **Raytheon Technologies** - Ammonia Comb. for Zero-Carbon Power ($3M / $3.75M)
- **GTI** - Investigation of Ammonia Combustion for Turbines ($3M / $4.2M)
- **GE Research** - GT-Scale RDC Demo at 7FA Cycle Cond. ($7M / $8.75M)

What will be done

- Develop combustion modules for F-class, aeroderivative and industrial scale turbines
- Develop retrofit technologies
- Apply to 100% hydrogen & natural gas / hydrogen blends
- Assess ammonia fuels
- Advance the application of rotating detonation combustion systems for power generation
- Advance H2 combustor technology to the next stage of testing & demonstration

Program Record

NO_x Emissions from Hydrogen Fueled Gas Turbines

- **Comprehensive literature survey**
- **Describes status of H_2 turbines**
- **Explains current biases in data that disadvantage hydrogen**
- **Peer reviewed**
- **Supports DOE's carbon free electric power goals**

Conclusions: *1.) Hydrogen turbines of the future will have comparable performance and emissions (NOx) compared to today's NG turbines. 2.) Appropriate standards for comparison, both scientific and legal, need to be developed for hydrogen.*

DOE Low NOx Targets and Hydrogen Fueled Gas Turbines

- Dr. Vince McDonell, UC Irvine; Director, UCI Combustion Laboratory
- Dr. Jeff Goldmeer, GE Gas Power; Emergent Technology Director – Decarbonization
- Dr. Pete Strakey, NETL Advanced Combustion Group Leader

NOx and Combustion (Gas Turbine) Technology
Historical Perspective and Path Forward with Hydrogen

Vincent McDonell

Director, UCI Combustion Laboratory

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www.UCICL.uci.edu

UCI Combustion Laboratory

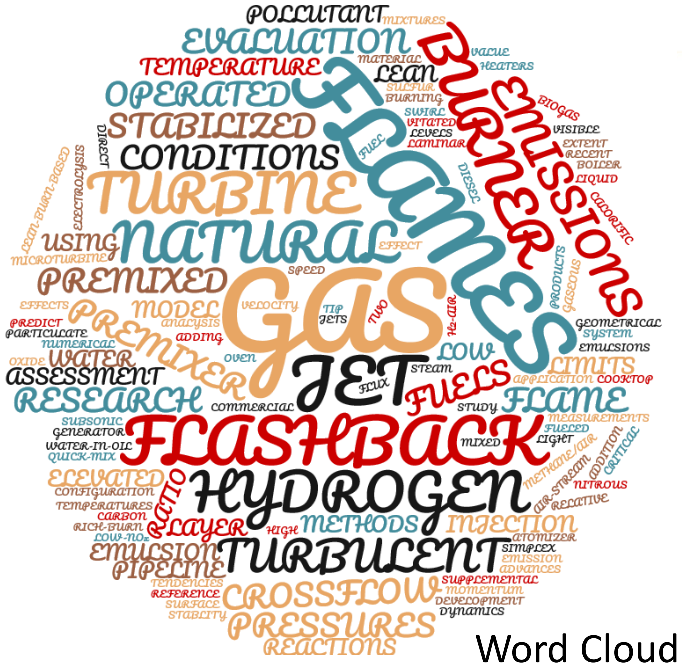
UCIrvine University of California

Advanced Power & Energy Program

15 Sept 2022

UCI Combustion Laboratory

- History
  - Founded in 1970 by Prof Scott Samuelsen
    - ✓ Reconcile conflict between Energy and the Environment
  - Initial focus on Aeroengines
  - Stationary Power/Alternative fuels
- High Hydrogen Content Fuels
- Extensive Experimental Research Facilities



Word Cloud of Recent Paper Titles

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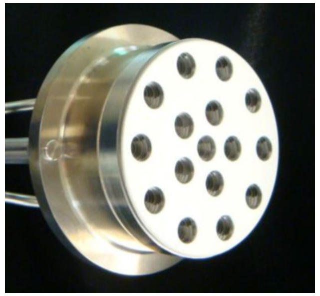
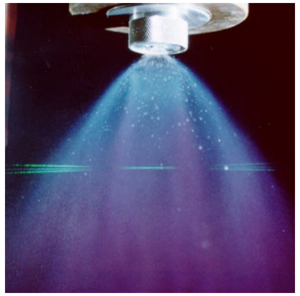
Research Capability

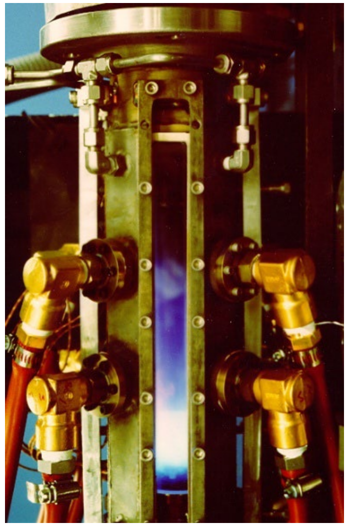
- **GAS TURBINE APPLICATIONS**

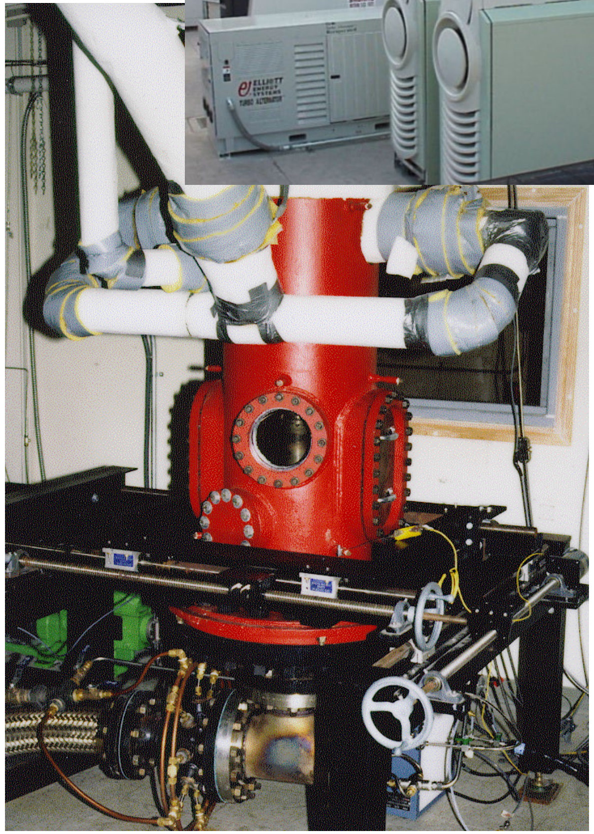



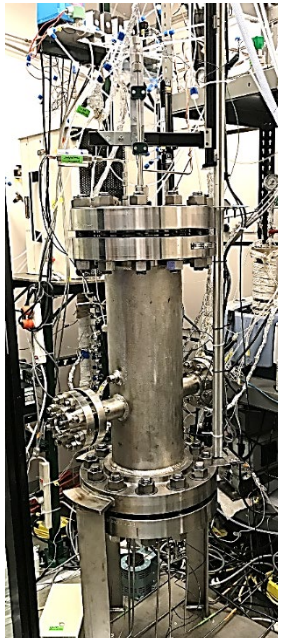
Component Study

Practical Engines

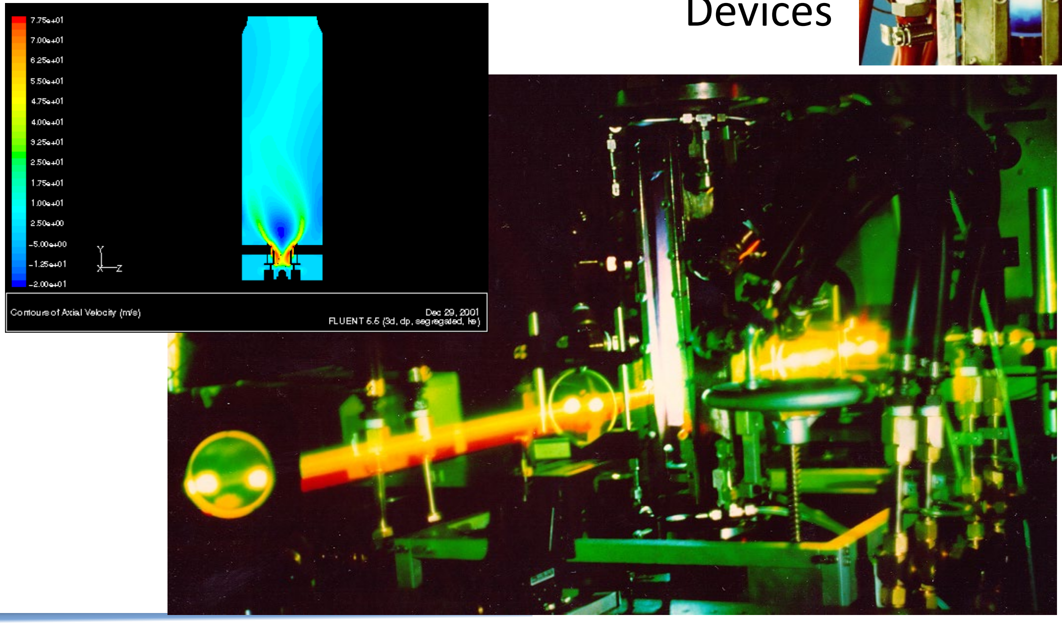
Model Devices







Simulation Of Practical Conditions
(1000 K, 15 atm, 2.2 kg/s)



Laser Diagnostics/
Modeling

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Perspective—High Hydrogen

Time	Project/Research Study Title	Scope
1997	Stand Alone Power Plant Running on Biomass Gas (EPRI)	Ignition delay times for lean H_2/CO/Air mixtures
2001-2005	Fuel Flexible Combustor for MTG (CEC)	Retrofit Capstone gas turbine engine for operation on 100% H_2
2003-2005	Correlation of Ignition Delay with IGCC Type Fuels (DOE UTSR)	Develop and Apply Flow Reactor to quantify ignition delay times at gas turbine premixer conditions
2005-2007	Micro-mixing lean premixed system for ultra-low NOx Hydrogen Combustion (Parker Hannifin/DOE)	Single/ multi injector lab tests for LBO, flashback, and emissions
2008-2010	Numerical and Experimental study of mixing processes associated with hydrogen fuels (DOE UTSR)	Detailed premixer mixing performance and companion detailed CFD analyses swirling and non-swirling flows to determine preferred turbulence and mixing models
2009-2013	Gas fuel interchangeability criteria development (CEC)	Develop and evaluate methods for predicting how fuel type impacts LBO, flashback, and emissions
2010-2012	Fuel Flexible Turbine System/Integrated Gasifier (Capstone/DOE)	Simulation and injector/combustor/engine testing for robustness to flashback
2010	Evaluation of low-swirl burner under high pressure conditions with varying hydrogen content fuels (LBNL/DOE)	High pressure testing and laser diagnostics of flow field for flame speed, flashback, LBO, emissions
2011-2014	Development of flameholding criteria for high hydrogen content fuels (DOE UTSR)	Developed test rig, data base, and correlation for flameholding tendencies at high P, T
2013-2016	Development of flashback criteria for high hydrogen content fuels (DOE/UTSR)	Developed test rig, data base, and correlation for flashback tendencies at high P,T
2014-2016	Application of chemical reactor networks to predict fuel composition impacts on burner stability and emissions (CEC)	Obtain data for industrial burners and apply simulation methodology to predict stability and emissions for high hydrogen content fuels
2017-2020	Impact of renewable fuels on appliance performance (CEC)	Obtain data for appliances and apply simulation methodology to predict stability and emissions for high hydrogen content fuels
2020-2023	Extending hydrogen tolerance while reducing emissions of appliances (Industry, SCG, ATCO)	Evolve burner systems to reduce emissions and extend operability of appliances
2021-2024	Development of 100% hydrogen fueled gas turbine systems (DOE, Industry)	Evolve fuel injection schemes to reduce emissions and extend operability of gas turbine systems
2022-2026	Examining the Effects of Hydrogen in End-Use Appliances for Large Commercial Buildings and Industrial Appliances (CEC)	Obtain data for commercial and industrial appliances and apply simulation methodology to predict stability and emissions for high hydrogen content fuels

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20+ years of research experience

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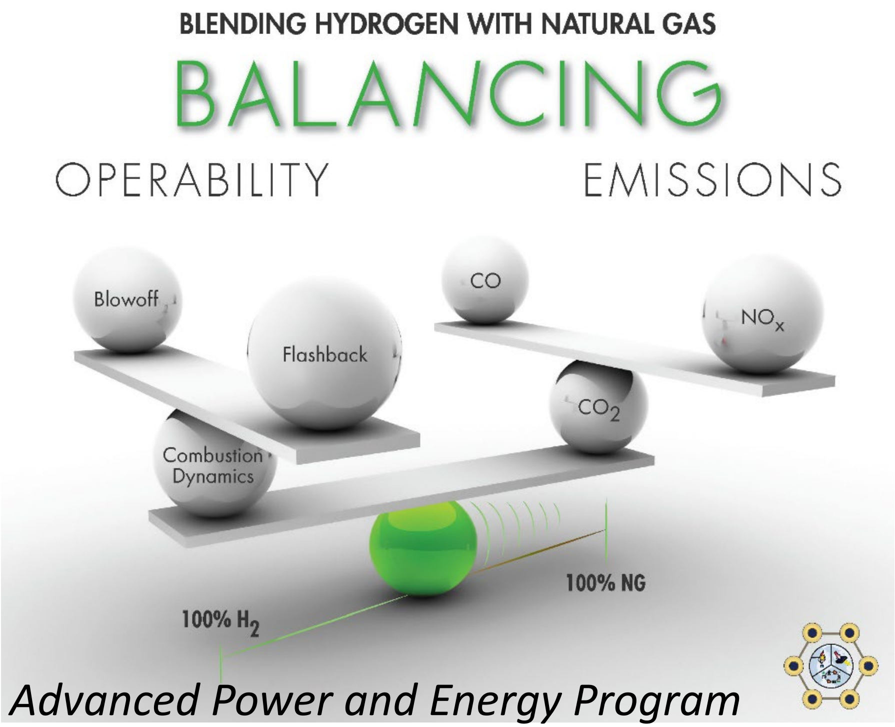
Perspective on Hydrogen or Hydrogen Addition to NG for GTEs

- **What about combustion related considerations?**

  - **Operability**
    - ✓ Wide flammability limits→ improved static stability limits
    - ✓ Autoignition?
    - ✓ Flashback?

  - **Emissions**
    - ✓ NOx Emissions (CO and CO_2 inherently eliminated)



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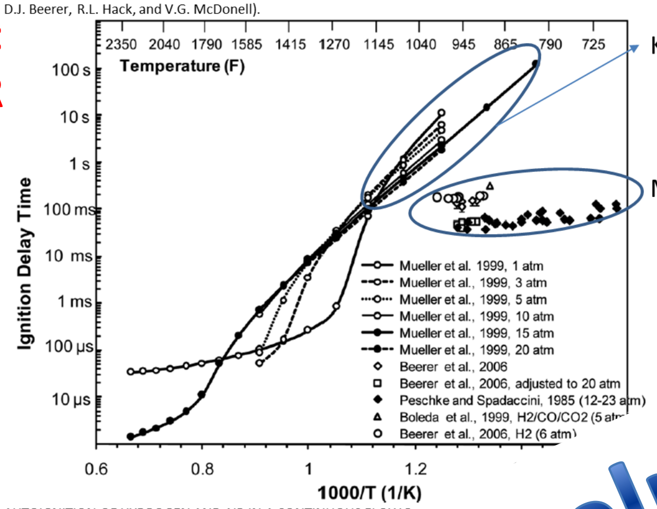
UCI Previous Work for US Department of Energy and Industry

H2 Ignition Delay:
DOE—FECM UTSR

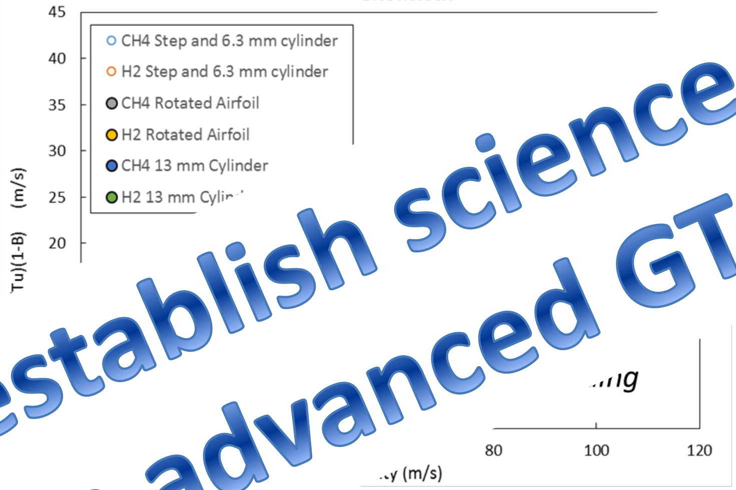
NEW SYNGAS/AIR IGNITION DATA AT ELEVATED PRESSURE AND COMPARISON TO CURRENT KINETICS MODELS (2007). *Combustion and Flame*, Vol. 149 (1-2), pp. 244-247. (E.L. Petersen, D.M. Kalitan, A. Barrett, S.C. Reehal, J.D. Mertens, D.J. Beerer, R.L. Hack, and V.G. McDonell).



AUTOIGNITION OF HYDROGEN AND AIR IN A CONTINUOUS FLOW
ASME J. Engr. Gas Turbines and Power, Vol 130, 051507-1

H2 Blowoff:
DOE—FECM UTSR

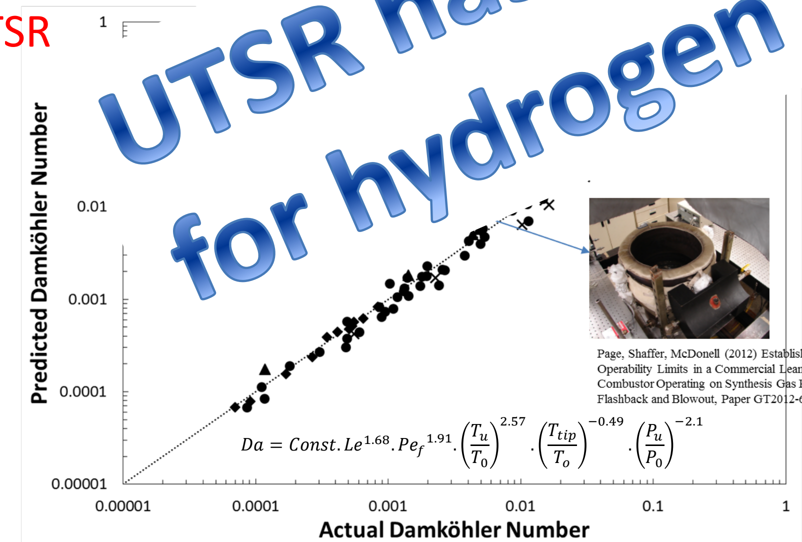
$$Da = \frac{\tau_{Physical}}{\tau_{Chemical}} = \frac{S_T(T_B/T_U)(1-B)}{U}$$



EN AND NATURAL GAS FLAMES AT GAS TURBINE PREMIXER CONDITIONS (2016).
Vol. 138(12), pp 121502-1 - 121502-9 (E. Sullivan-Lewis and V.G. McDonell)

UTSR has helped establish science for hydrogen use in advanced GTs

H2 Flashback:
DOE FECM UTSR

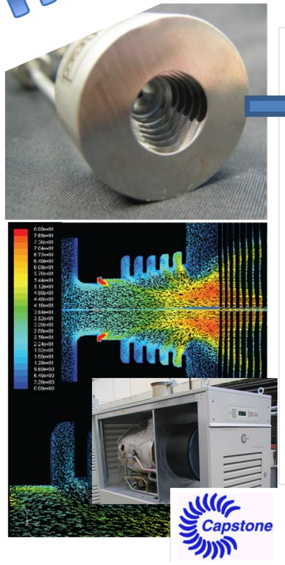


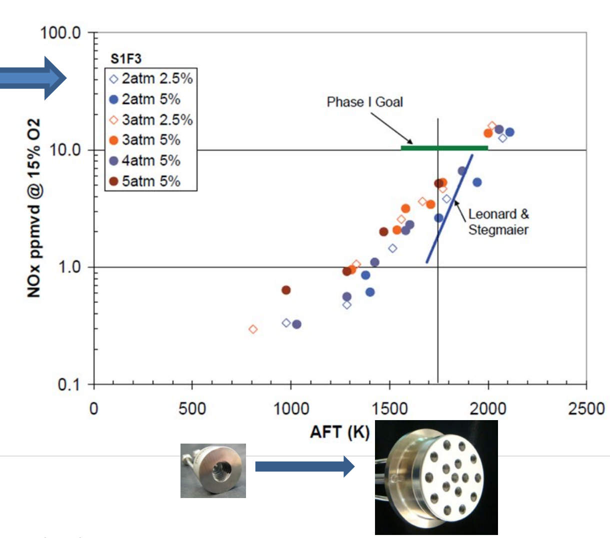
Page, Shaffer, McDonell (2012) Establishing Operating Operability Limits in a Commercial Lean Premixed Combustor Operating on Synthesis Gas Pertaining to Flashback and Blowout, Paper GT2012-69355

$$Da = Const.Le^{1.68}.Pe_f^{1.91}.\left(\frac{T_u}{T_0}\right)^{2.57}.\left(\frac{T_{tip}}{T_o}\right)^{-0.49}.\left(\frac{P_u}{P_0}\right)^{-2.1}$$

APPLICATION OF A TURBULENT JET FLAME FLASHBACK PROPENSITY MODEL TO A COMMERCIAL GAS TURBINE COMBUSTOR (2016).
ASME J. Engr Gas Turbines and Power. Vol 139(4), pp 041506-04156-8 (Alireza Kalantari, Elliot Sullivan-Lewis, and Vincent McDonell).

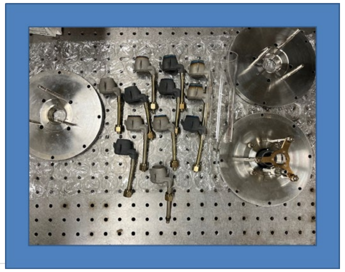
H2 Emissions
DOE—FECM
AHT





*Lee, Hernandez, McDonell, Steinthorsson, Mansour, Hollon (2009). Development of flashback resistant low-emission micro-mixing fuel injector for 100% hydrogen and SYNGAS fuels, Paper GT2009-59502, TurboExpo 2009.

Current FECM
UTSR effort!



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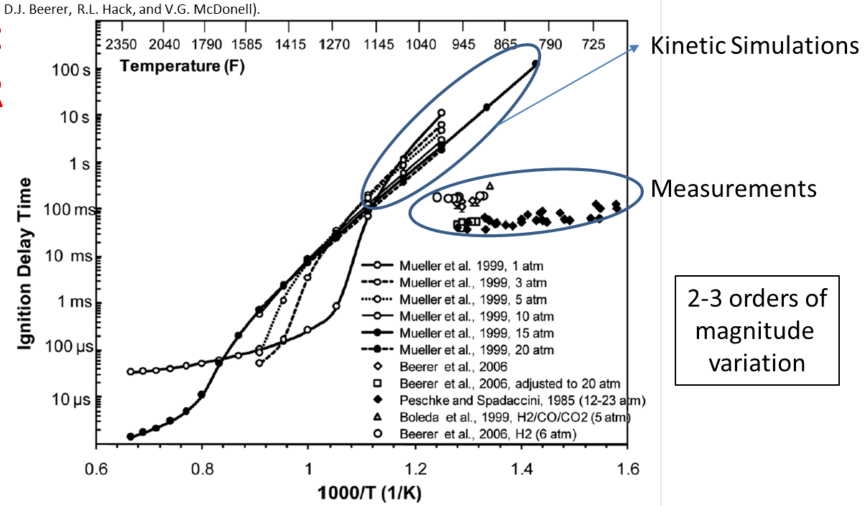

AUTOIGNITION OF HYDROGEN AND AIR IN A CONTINUOUS FLOW REACTOR WITH APPLICATION TO LEAN PREMIXED COMBUSTION (2008). *ASME J. Engr. Gas Turbines and Power*, Vol 130, 051507-1 to 051507-9, September (D.J. Beerer and V.G. McDonell).

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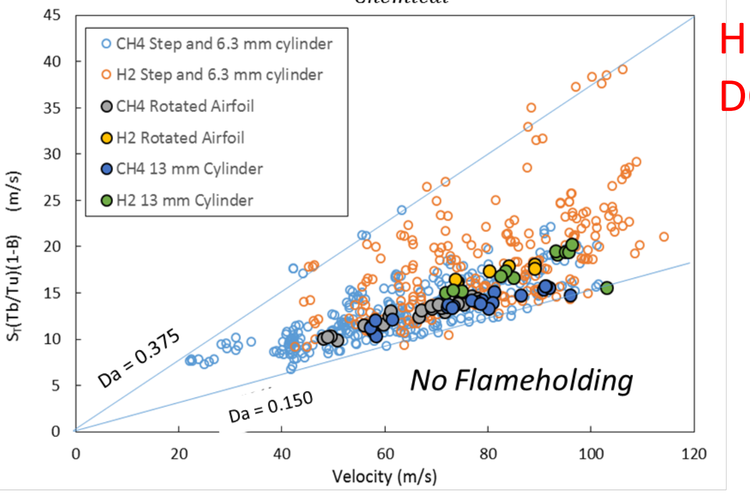
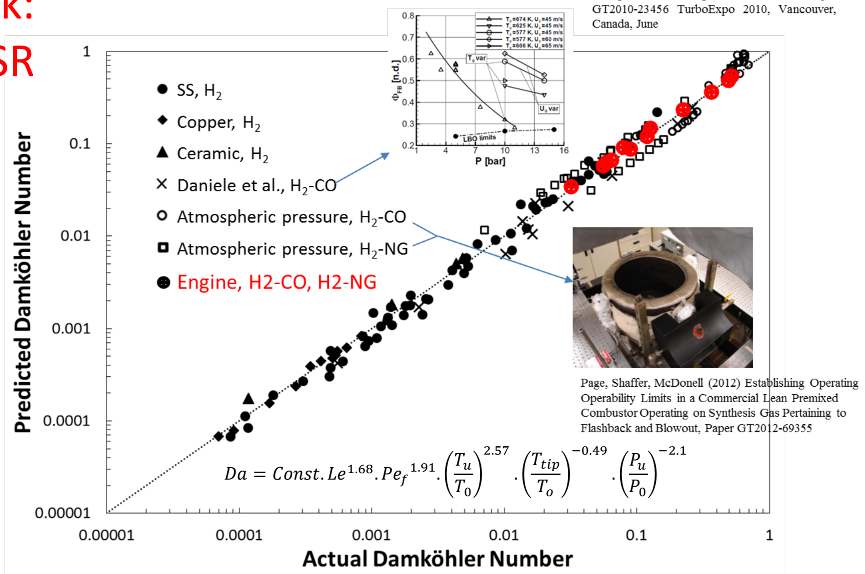


PREDICTING FLAMEHOLDING FOR HYDROGEN AND NATURAL GAS FLAMES AT GAS TURBINE PREMIXER CONDITIONS (2016). *ASME J. Engr Gas Turbines and Power*, Vol. 138(12), pp 121502-1 - 121502-9 (E. Sullivan-Lewis and V.G. McDonell)

H2 Flashback: DOE FECM UTSR

Daniele, S., Jansohn, P., & Boulouchos, K. (2010). Flashback Propensity of Syngas Flames at High Pressure: Diagnostic and Control. Paper GT2010-23456 TurboExpo 2010, Vancouver, Canada, June



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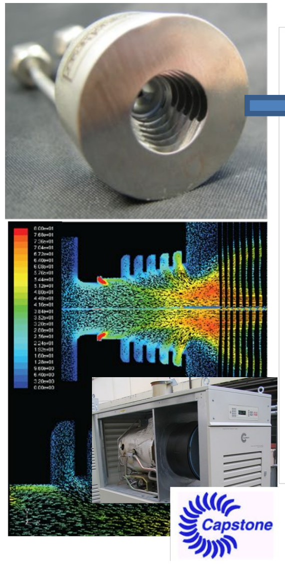
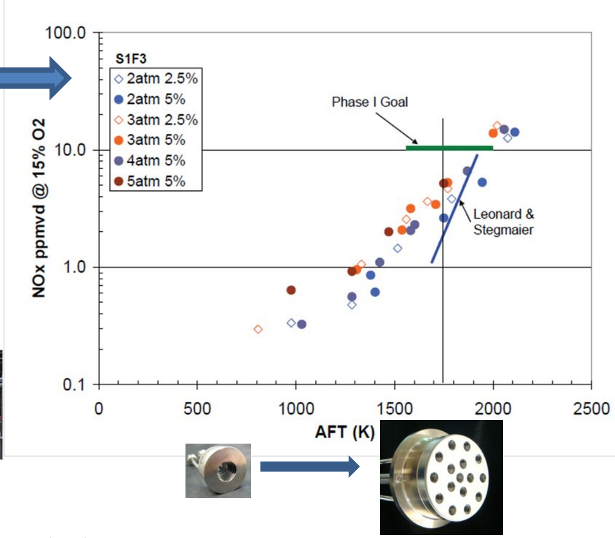
H2 Emissions DOE—FECM AHT





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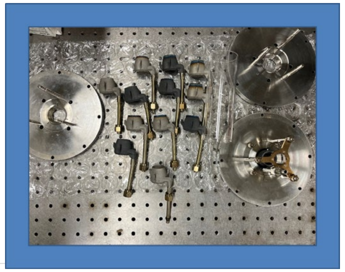

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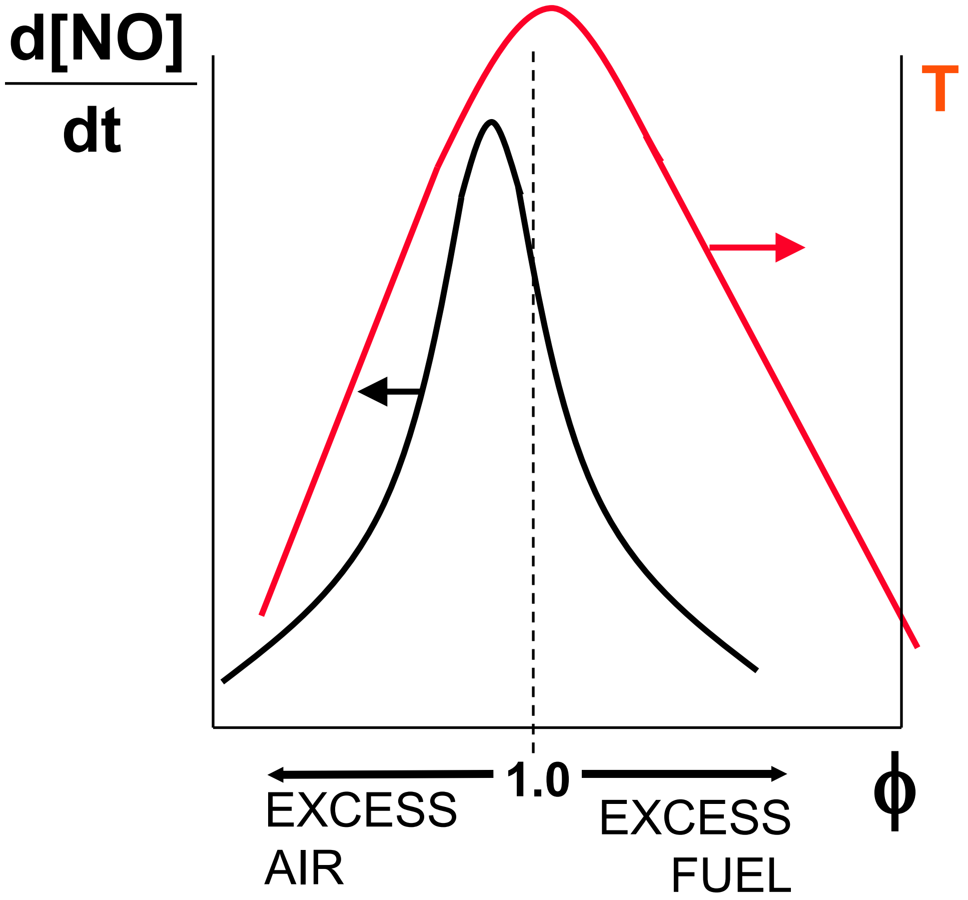
Background: Oxides of Nitrogen (“NOx”) emissions

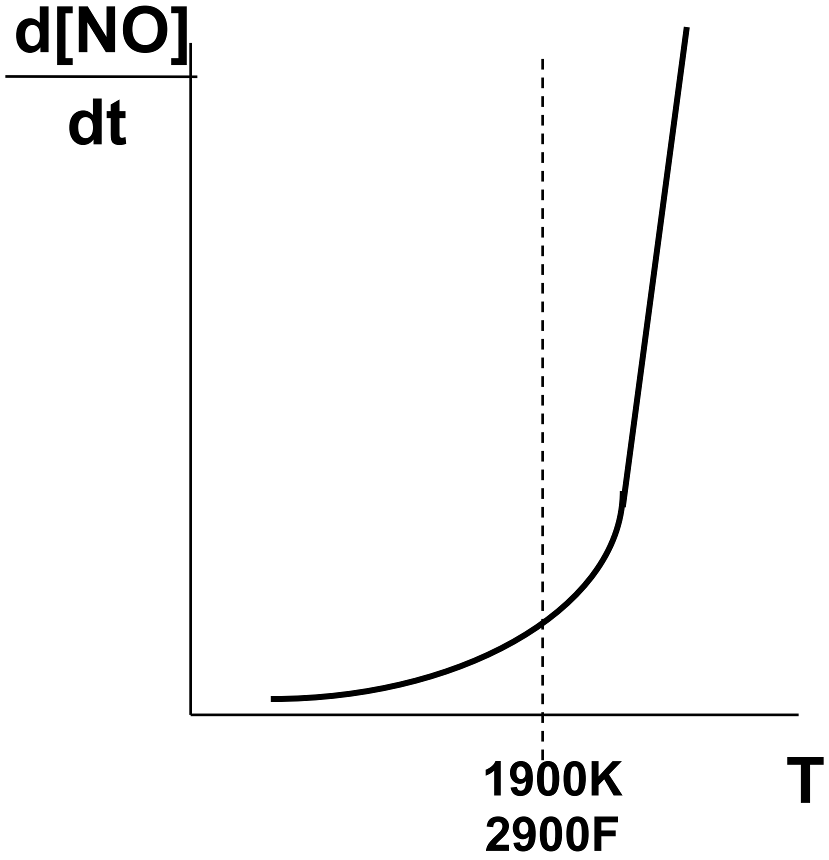
High Combustion Temperatures
→Enough Energy to Break Triple bonded N_2 molecule

- **NO Formation**

$$N_2 \text{ (Air)} + O \longrightarrow NO + N$$

$$N + O_2 \longrightarrow NO + O$$





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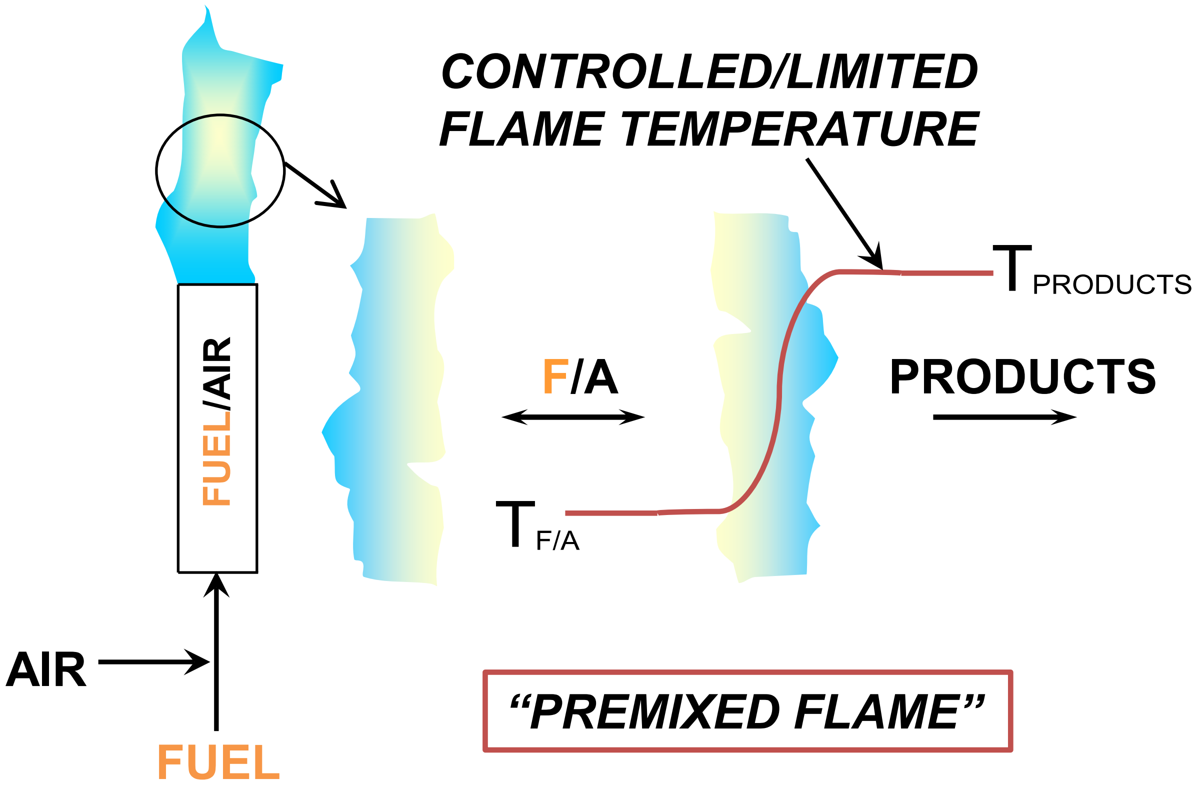
Background: Flame Structure

- Classical Flames

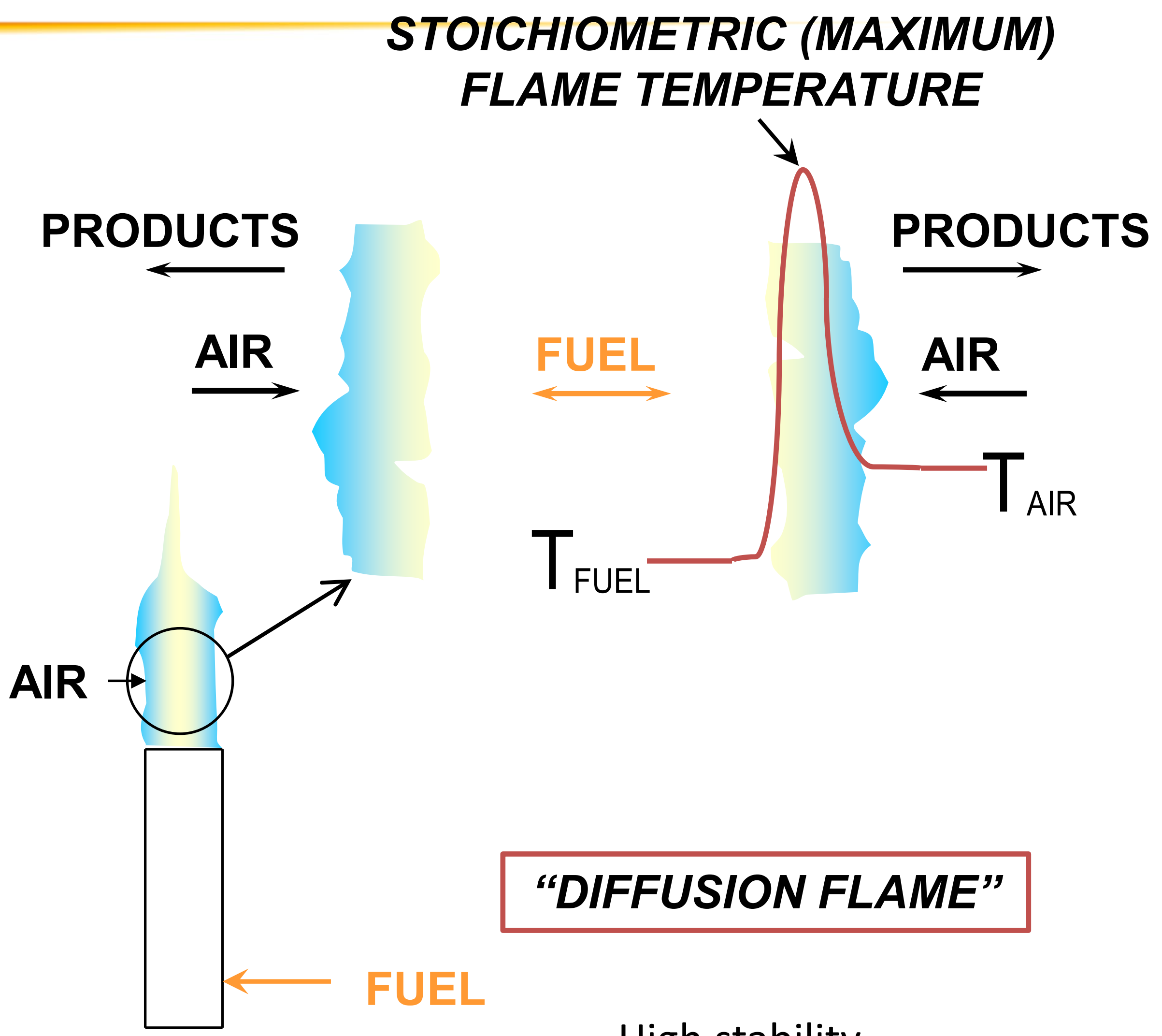


PREMIXED

"PREMIXED FLAME"

Low Emissions
Can be unstable

Typical of Low NOx burners



"DIFFUSION FLAME"

High stability
High NOx emissions

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Background: Other Aspects (Combustion Context)

- **Hydrogen vs Natural Gas**
  - Hydrogen requires less air to burn than natural gas
    - ✓ May need to adjust burners
  - Hydrogen has wider flammable limits vs natural gas
    - ✓ Potentially a good thing regarding flexible operation of gas turbines (easier staging, more stable flame)
  - For a ***given amount of excess air***, hydrogen burns at higher temperature than natural gas
    - ✓ Often pointed to as indication that NOx will increase with hydrogen
    - ✓ But combustion engineers can ***change excess air or other "levers" to control this***!
  - Hydrogen flame burns faster than natural gas (higher flame speed)
    - ✓ Hydrogen more stable
  - Hydrogen can burn closer to a surface than natural gas (smaller quench distance)
    - ✓ Hydrogen more stable
  - Hydrogen requires less ignition energy than natural gas
    - ✓ Hydrogen easier to ignite
  - Hydrogen has higher diffusivity than natural gas
    - ✓ Mixing?

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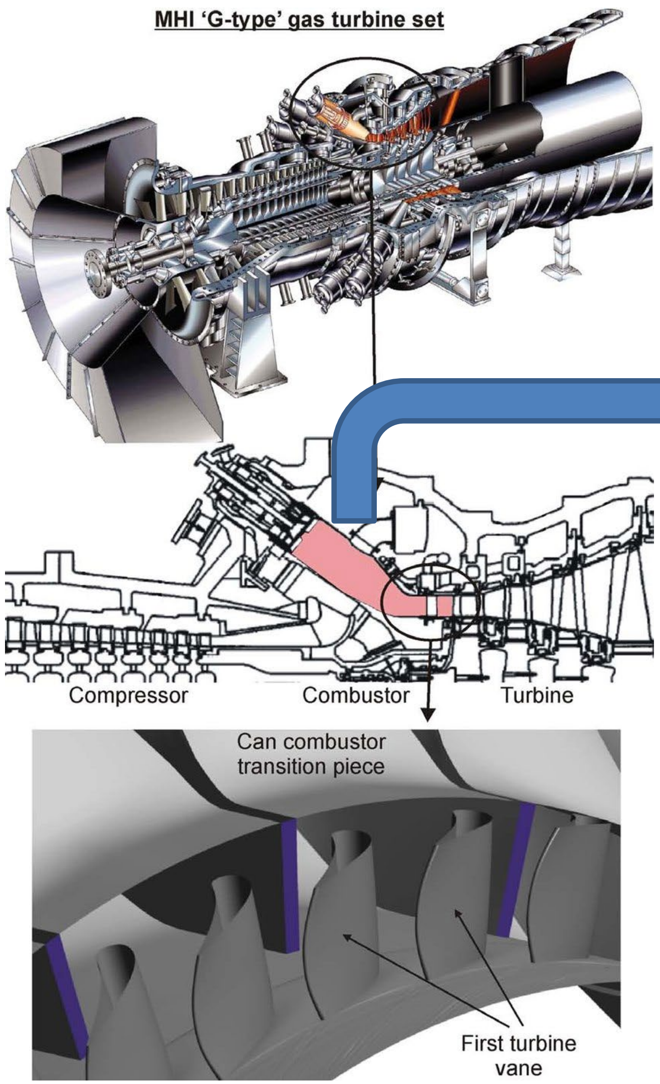
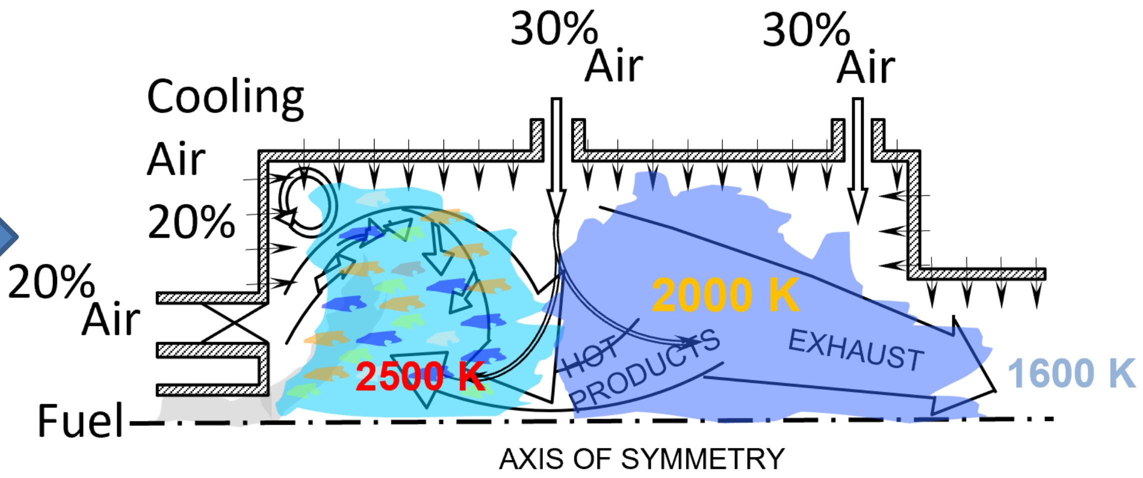
Gas Turbine Applications: Legacy Combustion



Aslanidou, et al. (2012). J. Turbomachinery, Vol 135(2)

Legacy "Diffusion Flame" Combustor



Turbine Inlet
Temperature
~1600 K

UCI Gas Turbine Combustion Short Course

Stable, Fuel Flexible
Decades of experience with all types of fuels (including H_2)

Not designed for "low emissions"

© UCI Combustion Laboratory 2022

Gas Turbine Applications: Emissions Regulations

- **Emission Regulations (EPA) for natural gas fired gas turbines**
  - **1979: 75 -- 150 ppm***
  - **1982: 75 – 150 ppm (some reconsideration for certain situations)**
  - **2004: add continuous emission monitoring**
  - **2006: 15, 25, or 42 ppm (depending on output of engine—most restrictive for large scale)**

- **Regional authorities can have more severe requirements**
  - **Example: SCAQMD Rule 1134**
    - ✓ **1989: 12, 15, or 25 ppm (depending on output of engine—most restrictive for large scale)**
    - ✓ **1995: 9, 12, 15, or 25 ppm**
    - ✓ **2022: 2, 2.5 ppm (on or after 1 Jan 2024)**

* Need to “reset” language for low carbon fuels……let’s use mass of pollutant per unit of fuel input or, even better, per useful output (electricity + heat)

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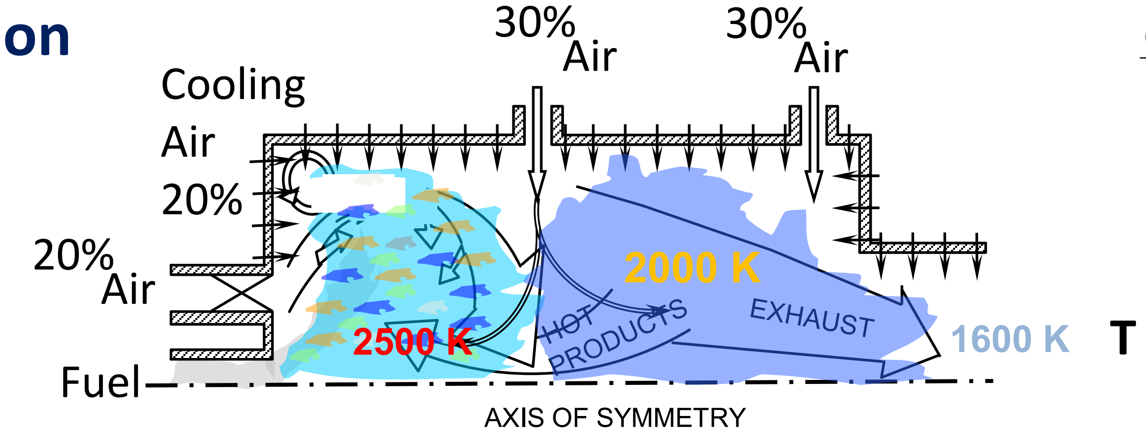
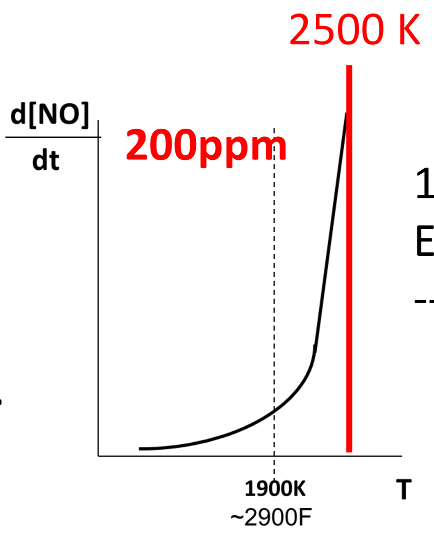
Gas Turbine Applications: Low Emissions

- **Legacy Diffusion**

Fuel + Air
Massflow = 30 lb/s

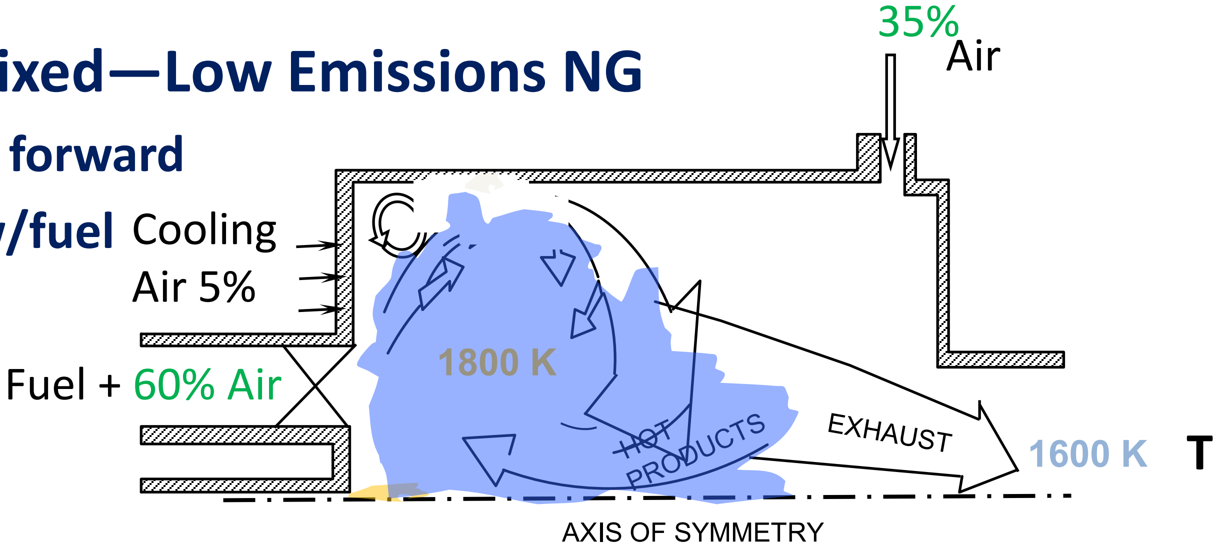


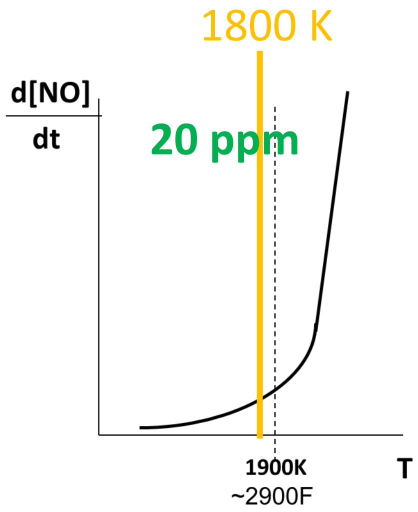


1979:
EPA Regs:
--NOx <75-150 ppm

- **Lean Premixed—Low Emissions NG**
  - **Move air forward**
  - **Premix w/fuel**

Fuel + Air
Massflow = 30 lb/s





1995:
SCAQMD Regs:
--NOx <9 ppm

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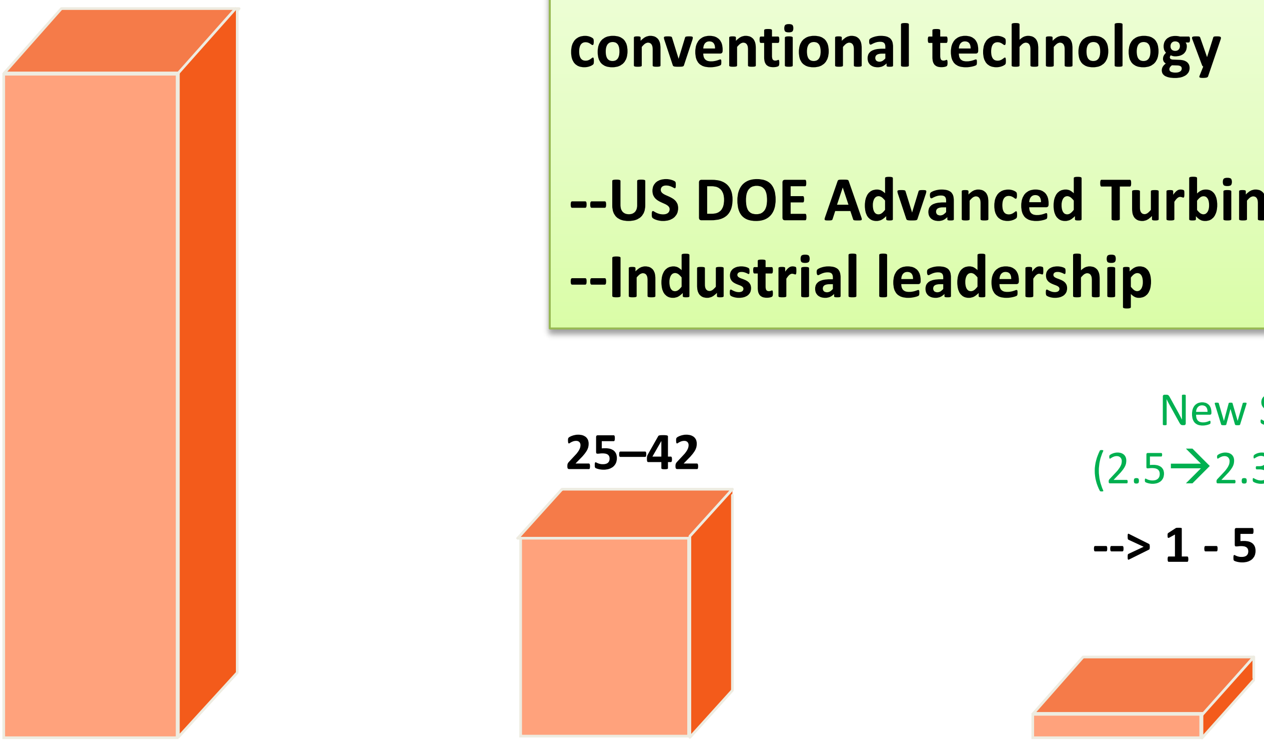
Gas Turbine Applications: Low Emissions

- Perspective

Lean Premixed combustion technology has led to a 50x reduction in NOx compared to conventional technology

--US DOE Advanced Turbine System Program
--Industrial leadership



New SCAQMD BACT 2020
(2.5→2.3 ppmvd @ 15% O_2 NOx)

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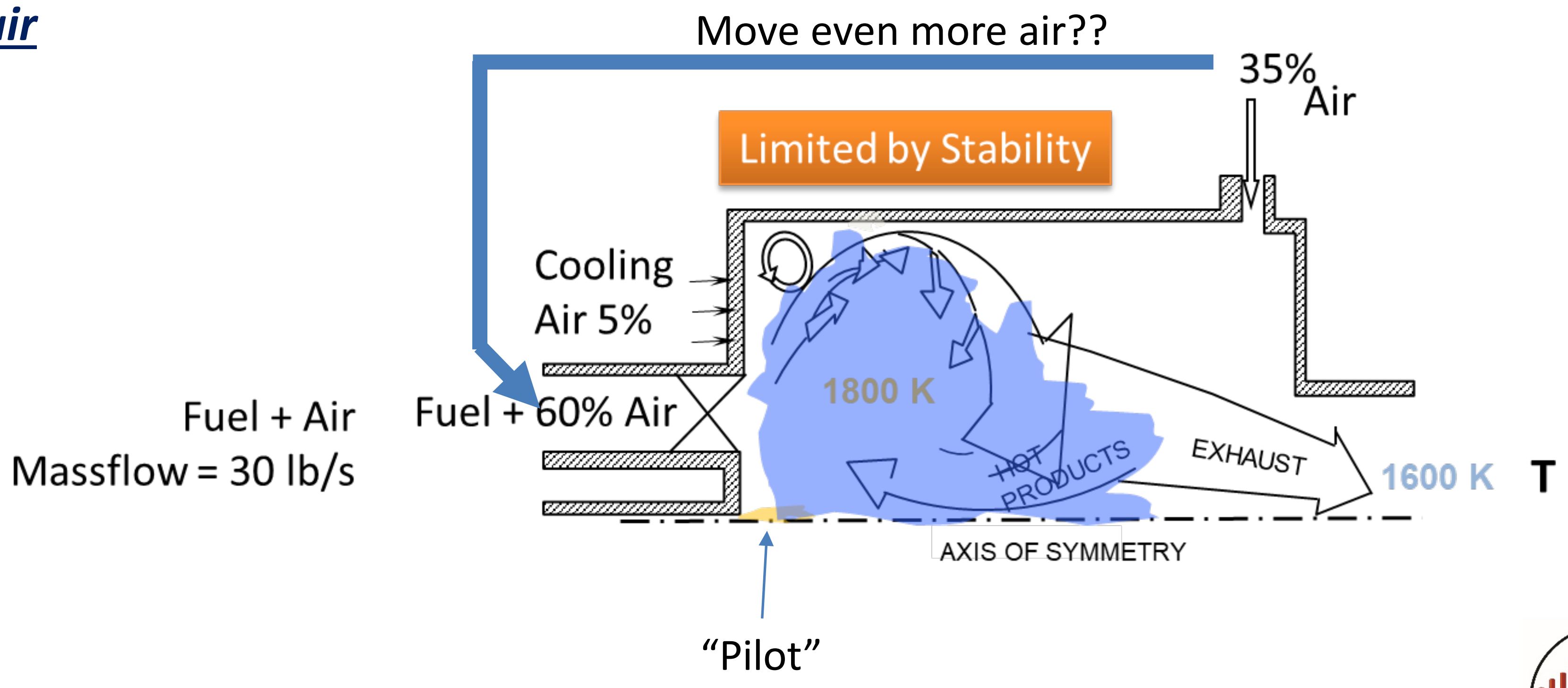
Gas Turbine Applications: Low Emissions

- Keep shifting more air to front?
  - "Lean Blow Off" limit is reached
    - ✓ strong function of fuel!
  - "Piloting"
  - Hydrogen reaction stable with ***much more air*** than natural gas!



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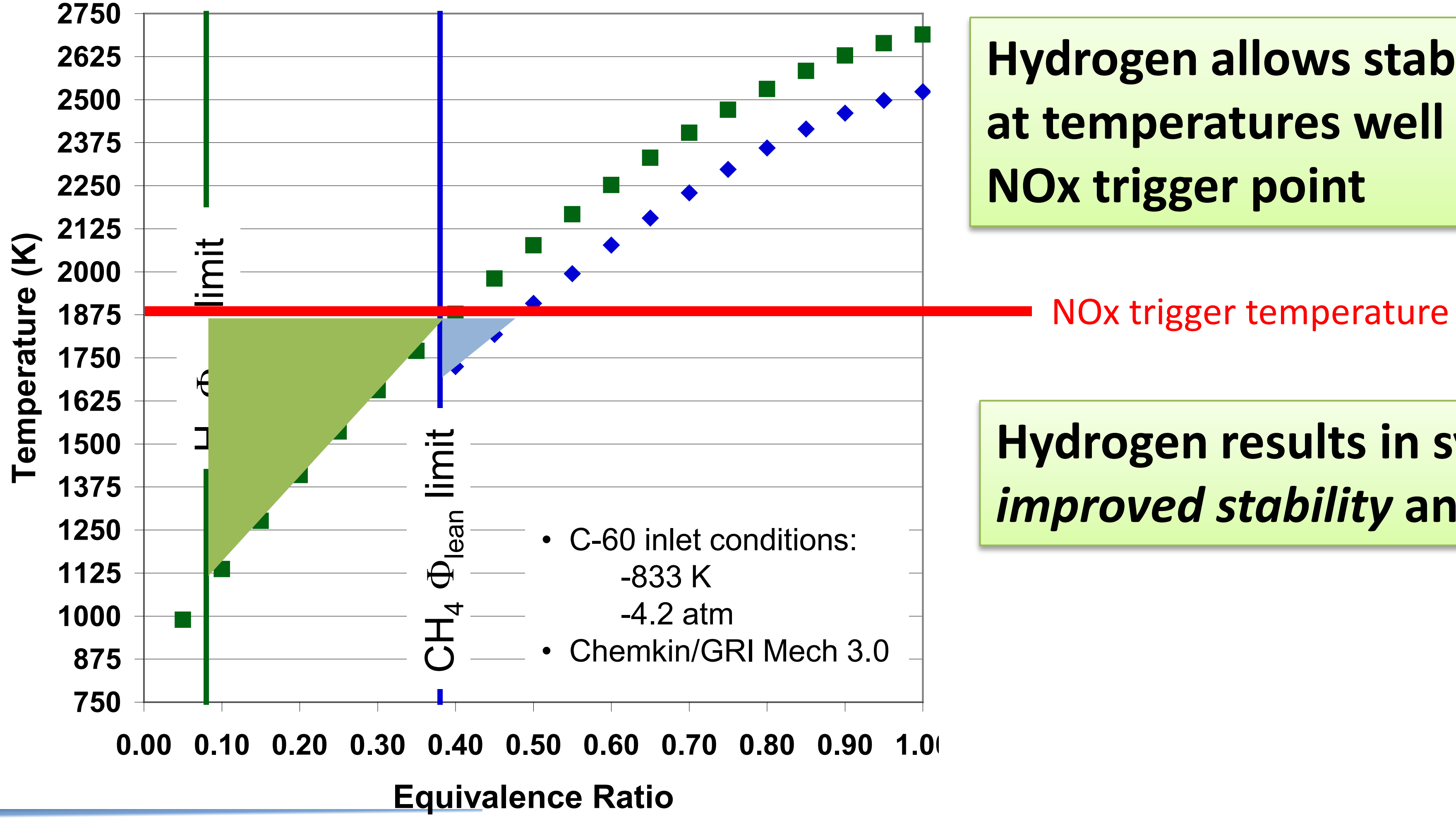
Gas Turbine Applications: Low Emissions

- **Benefit of wider flammability limits of hydrogen**
  - **Improved turndown**



Hydrogen allows stable operation at temperatures well below the NOx trigger point

Hydrogen results in synergy between *improved stability* and *lower emissions*

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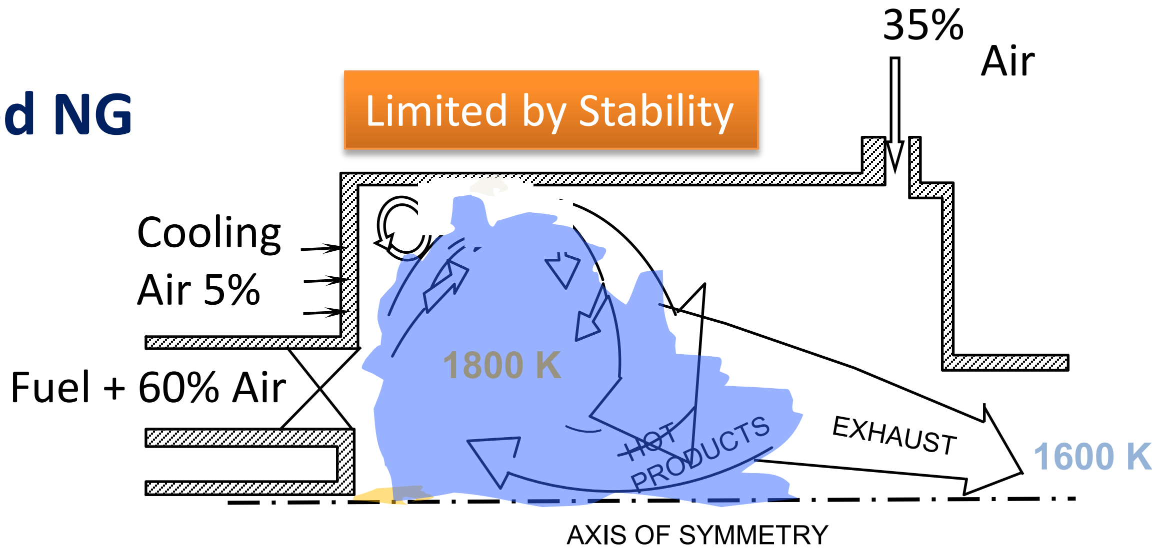
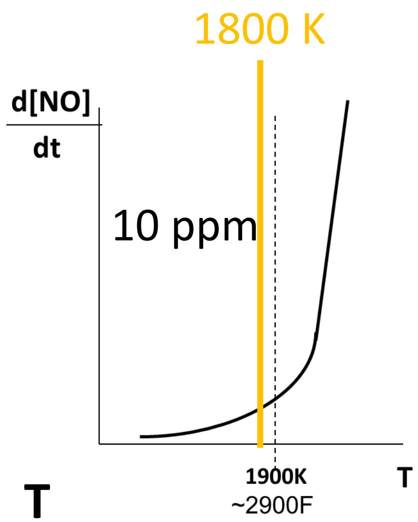
Gas Turbine Applications: Low Emissions

- **Lean Premixed NG**

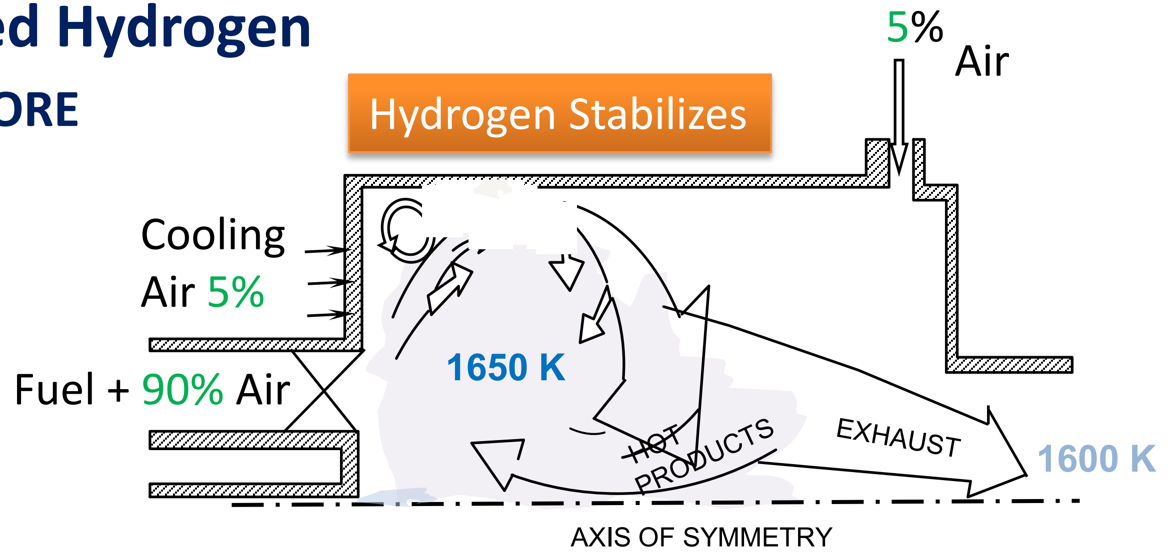
Fuel + Air
Mass flow = 30 lb/s

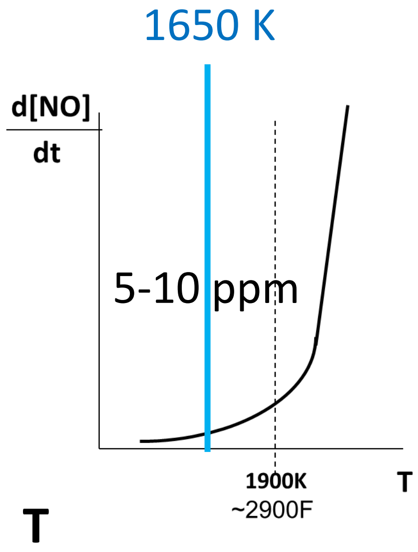




- **Lean Premixed Hydrogen**
  - **Can shift MORE air forward**

Fuel + Air
Mass flow = 30 lb/s





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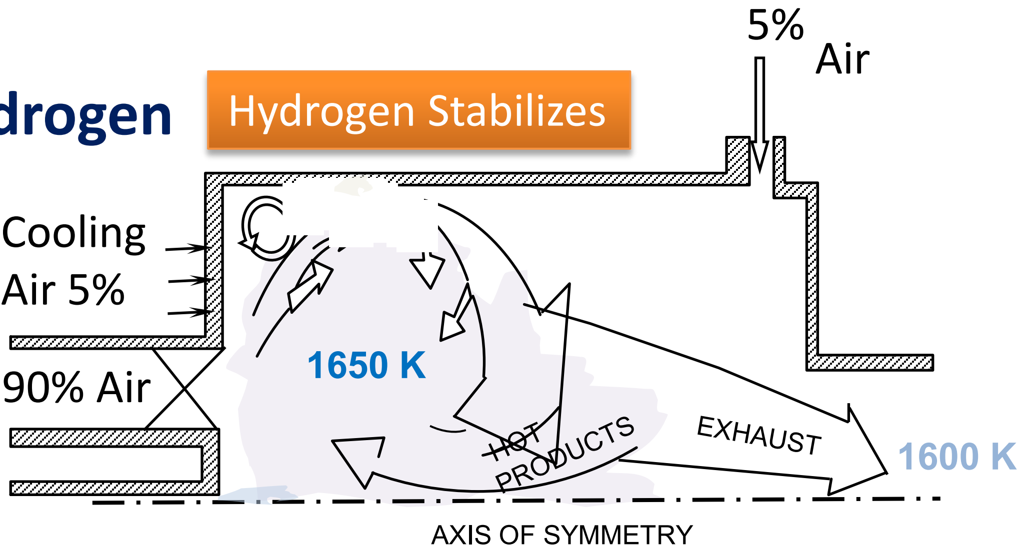
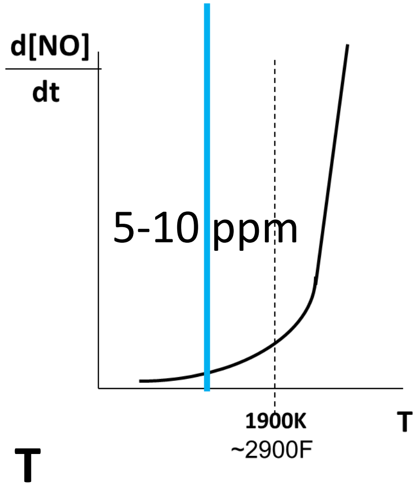
Gas Turbine Applications: Path to Low Emissions

- **Lean Premixed Hydrogen**

Hydrogen Stabilizes

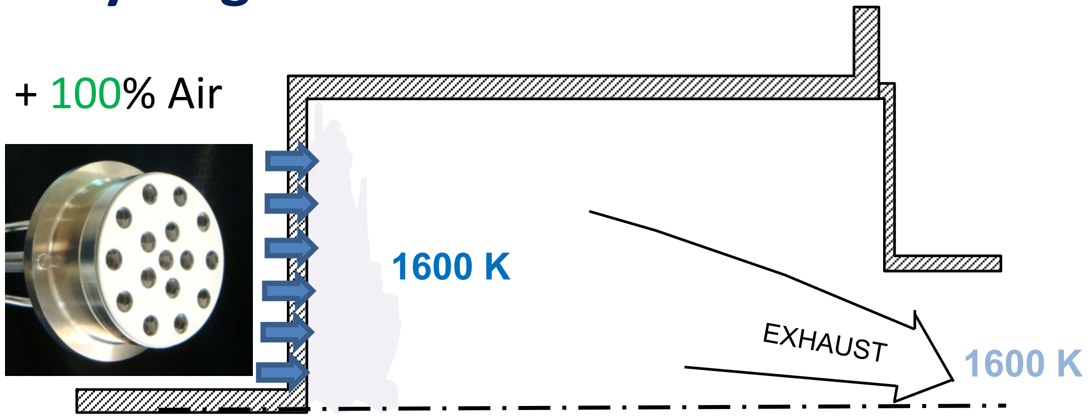
Fuel + Air
Mass flow = 30 lb/s

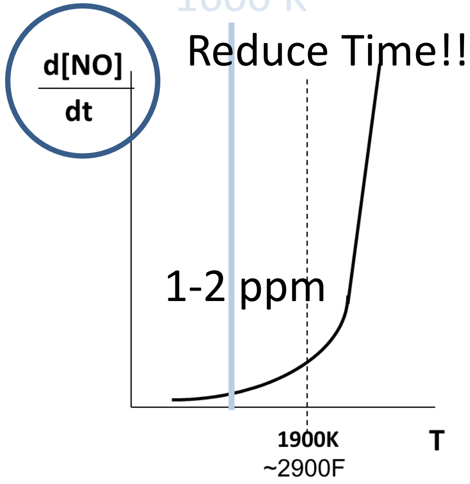




- **Lean Premixed Hydrogen "micromixers"**
    - **Short time**

Fuel + Air
Mass flow = 30 lb/s





SCAQMD
2024 limits

Micromix allows creative staging to attain turndown

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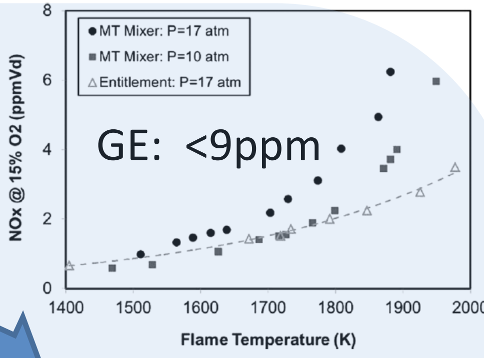
Gas Turbine Applications: Path to Low Emissions

Paths forward for hydrogen

- **Micromix strategies adopted by Solar, GE, MHI Kawasaki (others) to provide low emissions performance with ever increasing hydrogen content**
- **Ansaldo GT-26, 36 two stage combustion allows dilution to temper NOx formation**
  - H_2 burning in air plus CO_2 and water
    - ✓ Lowers flame temp

York, et al. (2013).



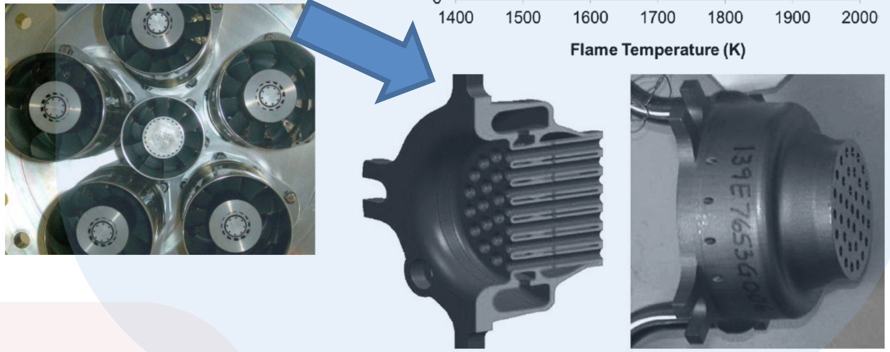
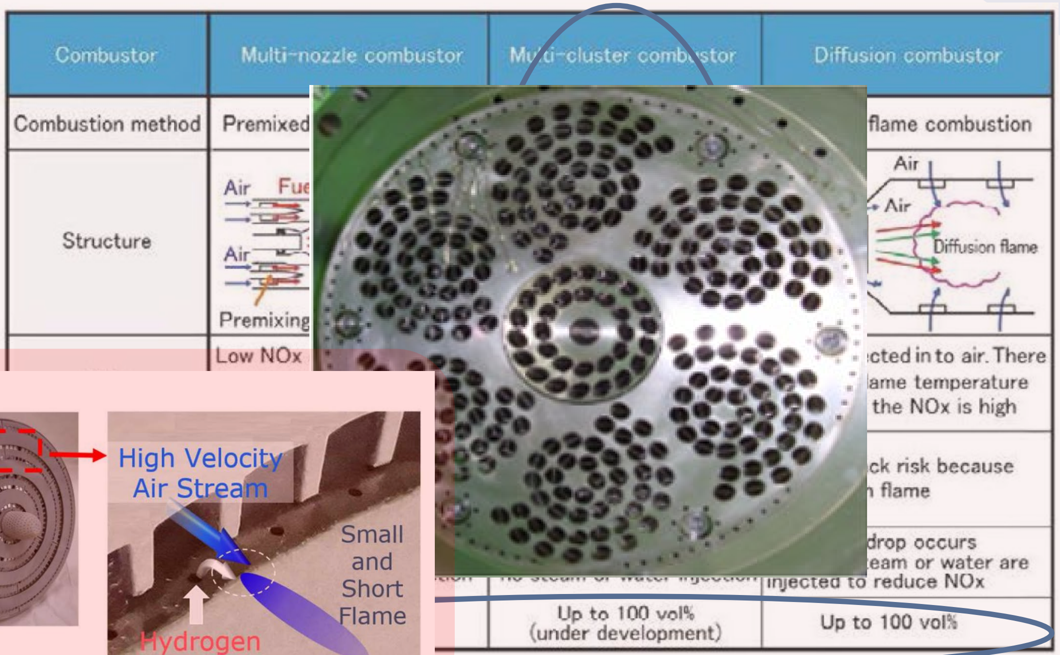
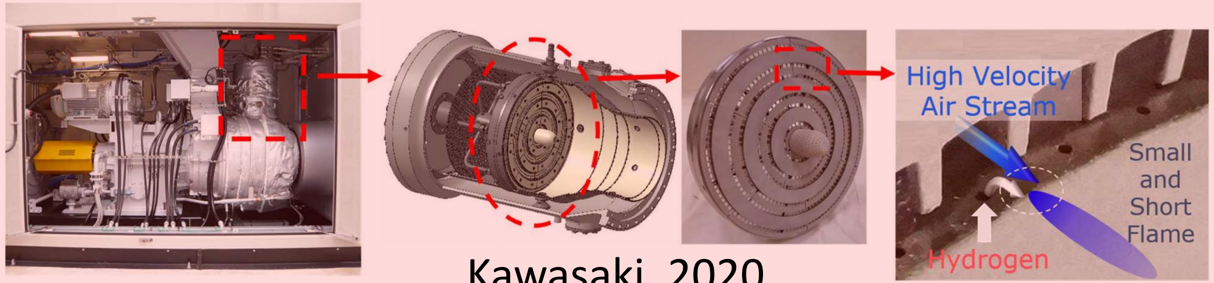


Fig. 2   Model cross section and photograph of small multitube mixer for high-hydrogen fuel

MHPS

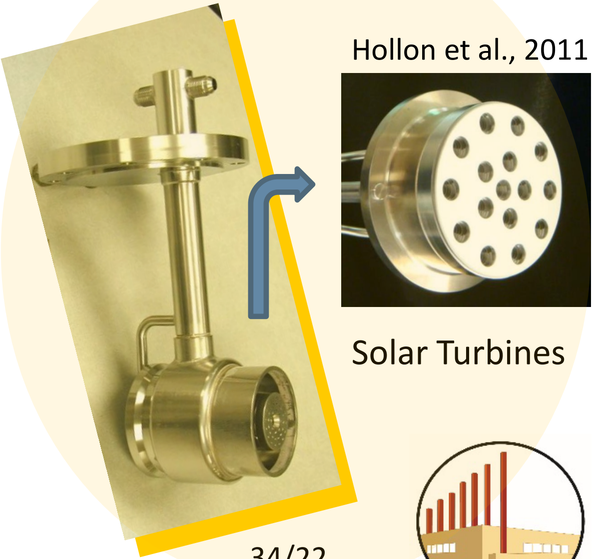


MHPS (2019). H_2 Power Generation Handbook



Kawasaki, 2020

Hollon et al., 2011



Solar Turbines

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Path to Low NOx Emissions

- OEMs are on track for technology evolution to reach low emission combustion on 100% hydrogen
- Lessons learned from low emission natural gas systems
- They have *several levers* to ensure NOx targets will be met
  - Combustor technology (e.g., fuel/air staging, EGR, micromix)
  - Engine controls
  - Combustor flow splits, piloting
  - Post combustion clean up
- Technoeconomics will dictate best path forward

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Closing Thoughts

- Gas turbines have operated reliably on hydrogen for decades
- Low emission technology for NG successfully reduced NOx by 50 times
- Hydrogen has beneficial features relative to NG that can be expoited
- Combustion science has helped address operability concerns
- OEMs are waiting for market signals to justify continuing investments
  - Recent investments by DOE and others are bolstering the market
  - Latest ASME Gas Turbine conference showed the collective commitment by the OEMs to advance high hydrogen systems
- Any fuel switch at existing site may be bound by existing permit limits
  - Up to 20-30% by volume→adjust levers
  - Beyond 30% →hardware changes which is a capital investment
- No "show-stoppers" from a technology viewpoint

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GE Gas Power – hydrogen experience

US DOE HQIQ Webinar – September 15, 2022

Dr. Jeffrey Goldmeer
Emergent Technologies Director - Decarbonization
GE Gas Power

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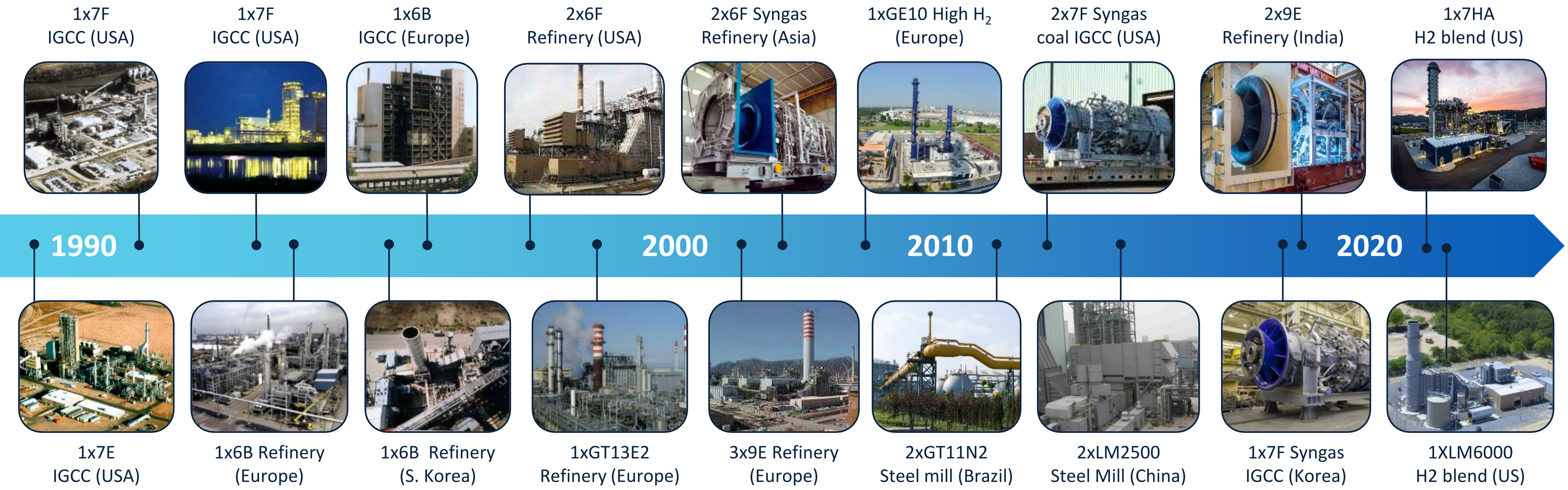
Hydrogen experience

Decades of experience with hydrogen fuel



GE has more than 100 gas turbines with more than 8 million operating hours on fuels containing hydrogen

© GE 2022

7HA Hydrogen Blending & Operation Demonstration
Long Ridge Energy Terminal, Hannibal, OH – April 22, 2022

We engineer cleaner, more accessible energy that people depend on, powering growth and prosperity everywhere.

© GE 2022

Green Hydrogen Demonstration Project Kick-off at Brentwood Power Station on Long Island, NY – Oct 2021

Results are to be released the week of 9/19/22

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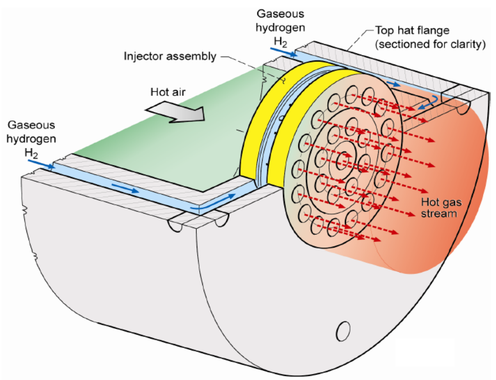
Combustion technology … journey to 100% hydrogen

Journey to 100% Hydrogen

Development of micromixer technology

Lean Direct Injection (LDI)

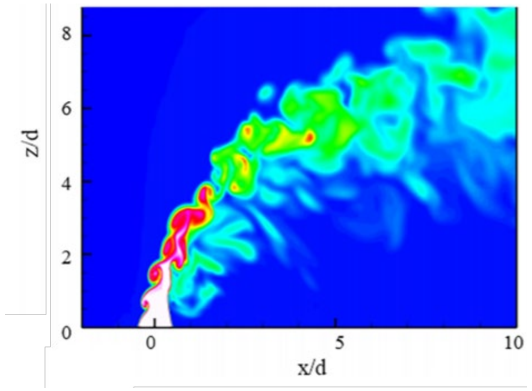


NASA low emissions LDI hydrogen combustor assembly

Marek, C., et al., "Low Emission Hydrogen Combustors for Gas Turbines Using Lean Direct Injection", 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA-2005-3776, 2005.

+

Jet in Cross Flow

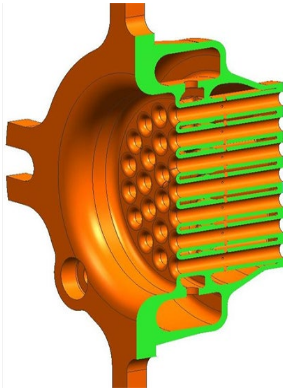


Numerical simulation of injection cross in cross flow mixing

M. Zhang, L., and Yang, V., "Flow Dynamics and Mixing of a Transverse Jet in Crossflow – Part 1: Steady Crossflow", *Journal of Engineering for Gas Turbines and Power, vol. 139, 2017.*

→

Multi-tube mixers



Advanced premixer technology development

2005 | 2016 | 2018

Swozzle based architectures

Target premixing and flashback tolerance for NG

Hydrogen limits

- DLN 2.6 ~5% (vol)
- DLN 2.6+ ~15–18% (vol)

DOE High-H_2 program*

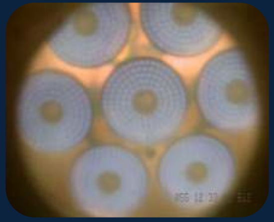
Target premixing and flashback tolerance for H_2

Small prototype

Additive

Prototype fuel nozzle

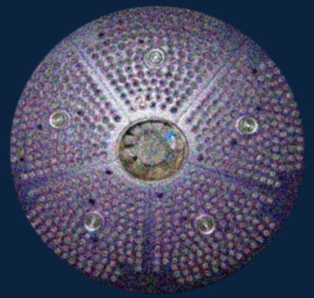
Full head end combustion test



Demonstrated single digit NO_x emissions at F-class temperatures and pressures

Demo

7HA.01 TS7



DLN 2.6e commercial operation in 2021

- This technology can be applied to natural gas or H_2 fuels…decouples flashback, premixing and dynamics
- Demonstrated capability to **50%** (by vol) H_2

*US Department of Energy under Cooperative Agreement DE-FC26-05NT42564

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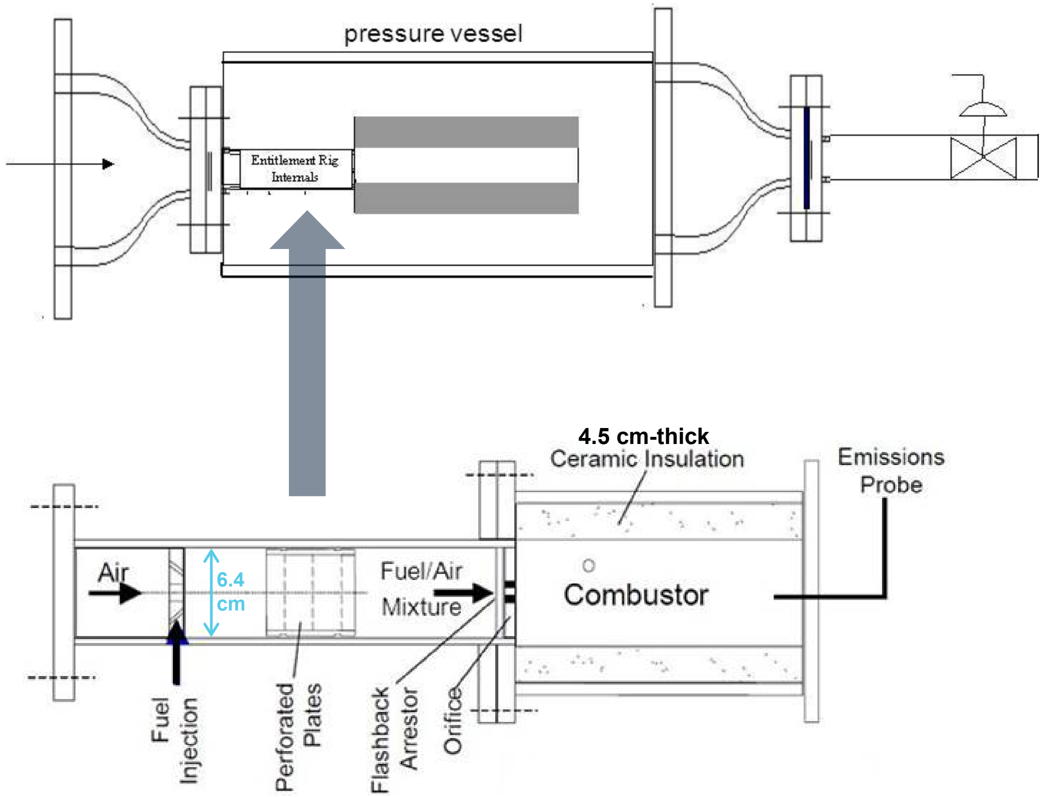
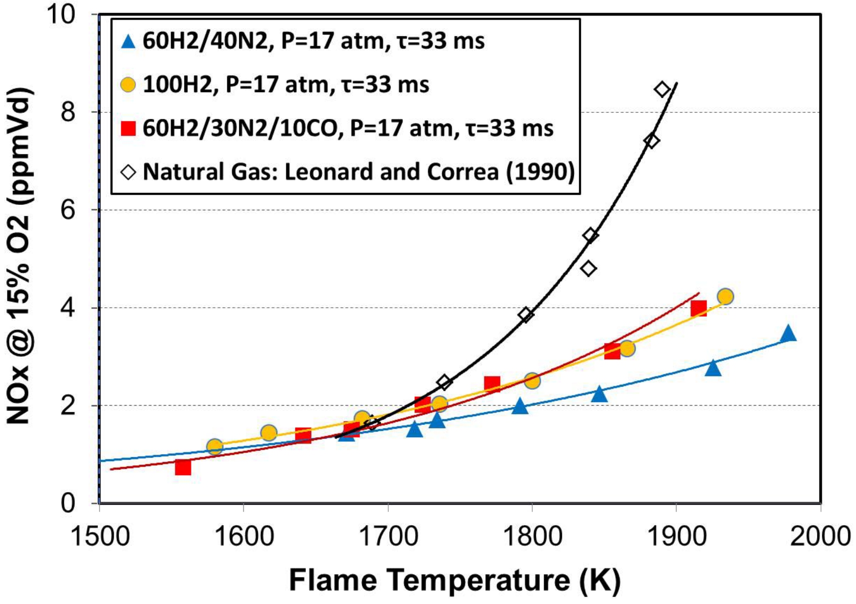
GE advanced combustion technology

DOE High H2 turbine program – NOx entitlement tests



NOx emissions from perfectly premixed combustion



Source: York, Ziminsky, and Yilmaz, “Development and Testing of a Low NOx Hydrogen Combustion System for Heavy-Duty Gas Turbines”, *Journal of Engineering for Gas Turbines and Power*, 2013.

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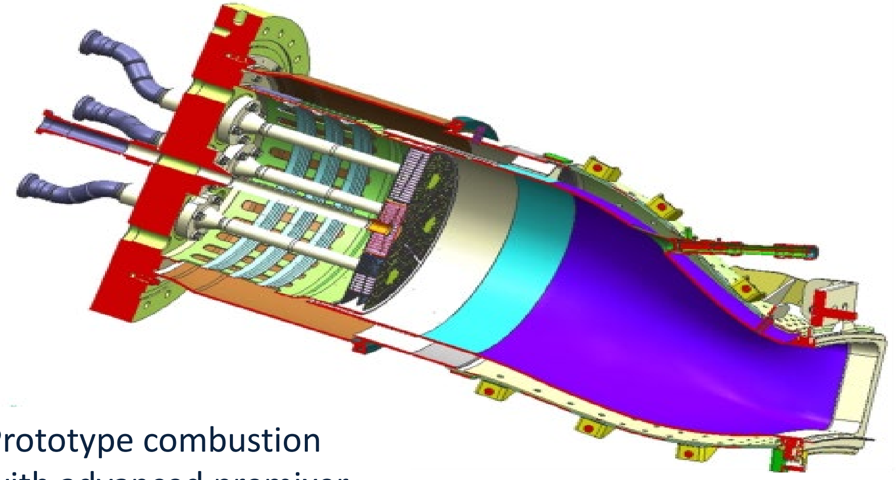
GE advanced combustion technology

DOE High H2 turbine program

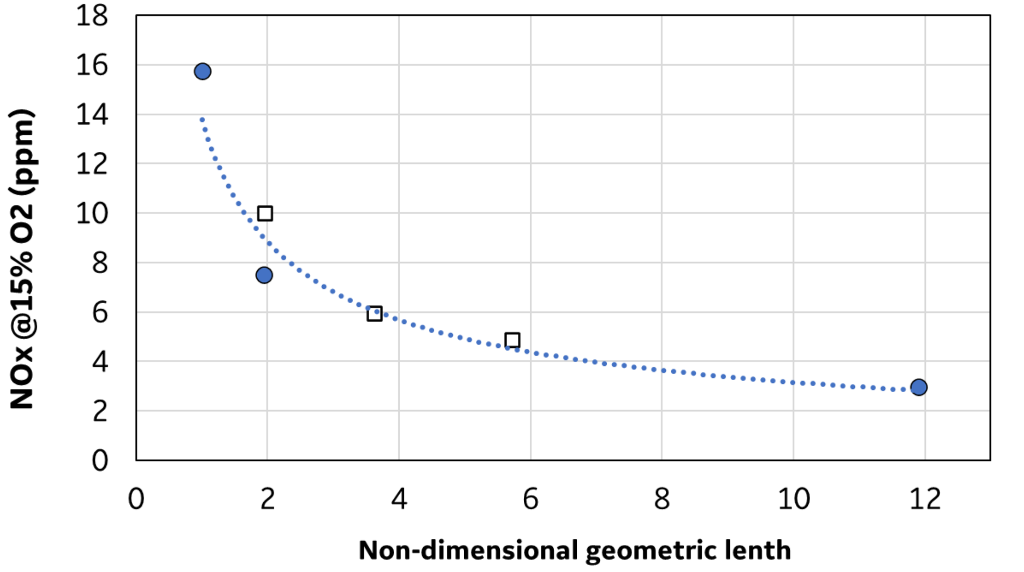
High H2 turbine program:

- Micromixer full can rig: 30 tests and 150+ fired hours with >90% H2 by volume total reactants
- Single digit NOx (6 ppm) with H2-N2 fuel at F-class conditions



Prototype combustion with advanced premixer

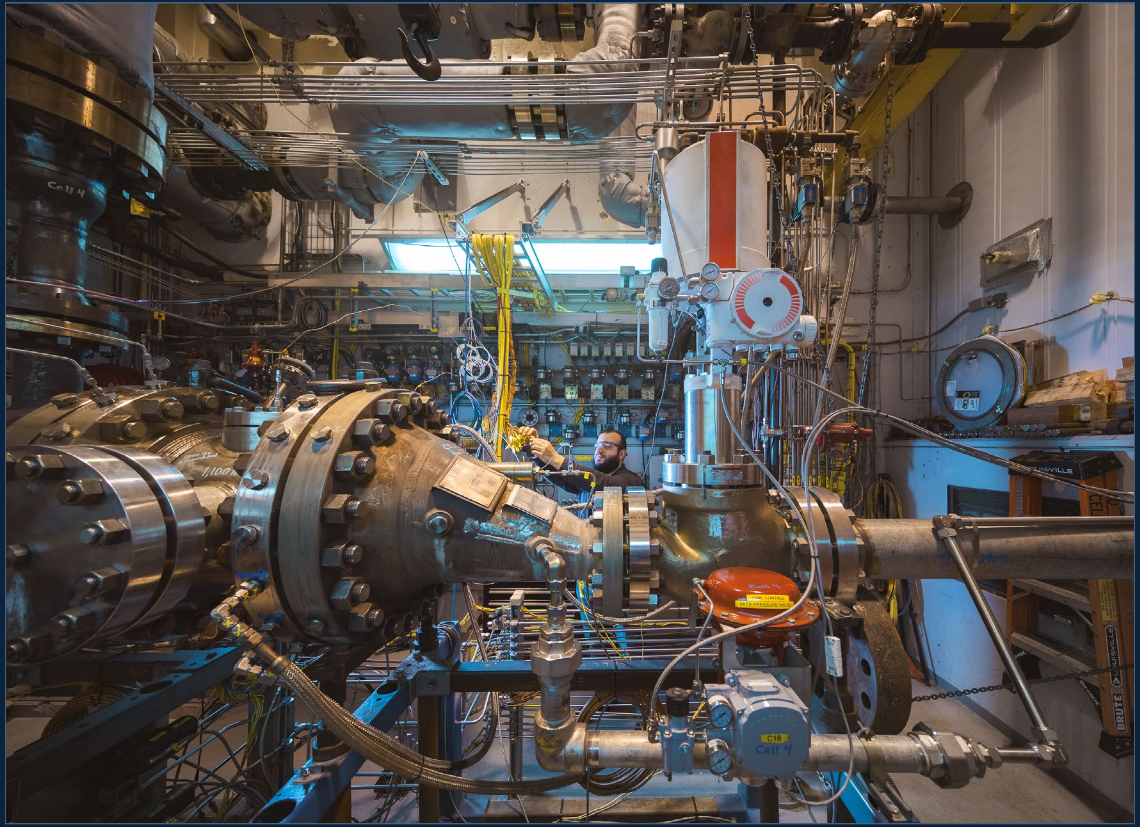
Lab test NOx data



US DOE funding of GE's hydrogen combustion technology

- The US DOE has selected a GE Gas Power proposal to develop and test a retrofittable combustion module for operation with natural gas/hydrogen fuel mixtures ranging from 100% natural gas levels up to 100% hydrogen. This will project will be based on micromix and axial fuel staging technologies.

- GE's goal is to produce **< 25ppm** NOx with a stretch goal of **9ppm** NOx. (Available emissions control technology can reduce NOx from 25ppm to < 3ppm from the power plant stack.)



https://www.energy.gov/fecm/articles/additional-selections-funding-opportunity-announcement-2400-fossil-energy-based
https://www.ge.com/news/press-releases/ge-doe-accelerating-the-path-towards-100-hydrogen-combustion-in-gas-turbines

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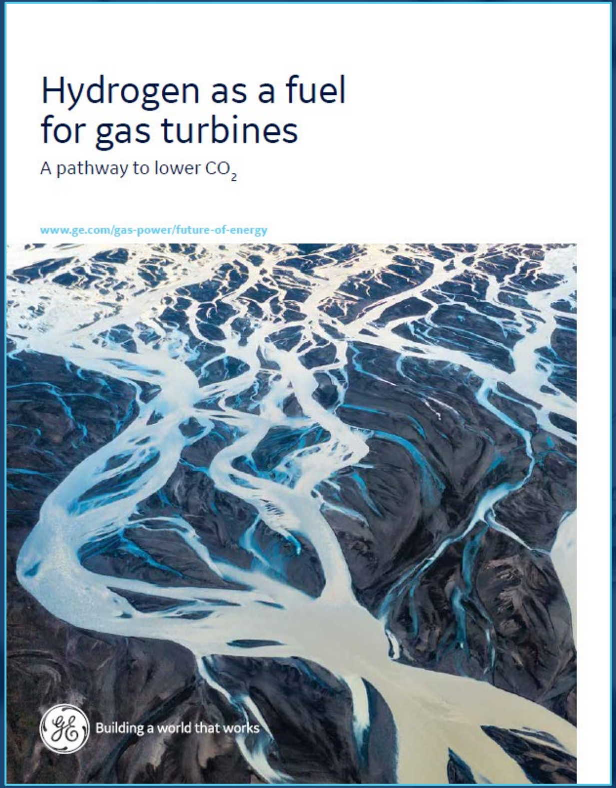
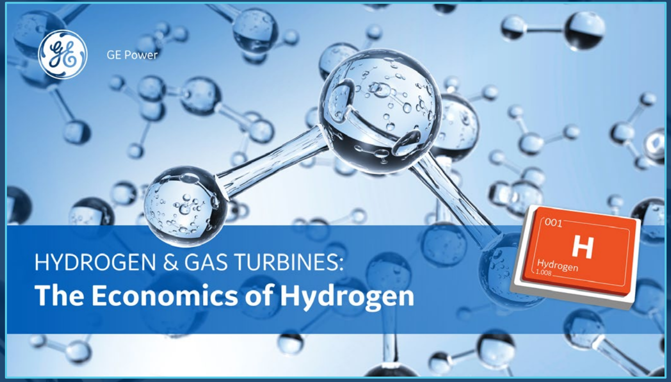
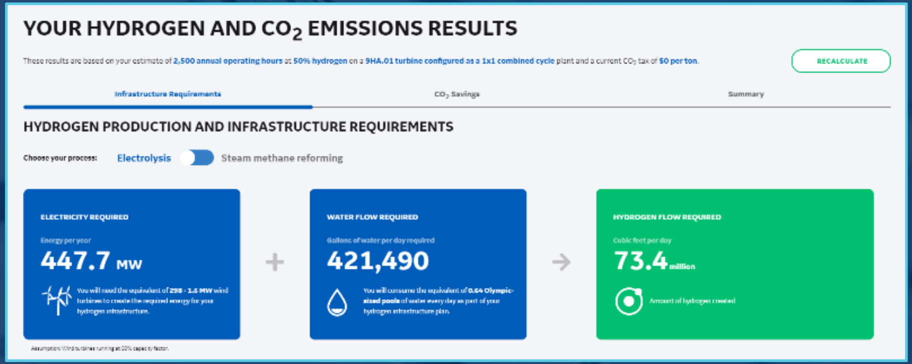
For more information: www.gepower.com/hydrogen



White paper



Webinars



Carbon emissions calculator

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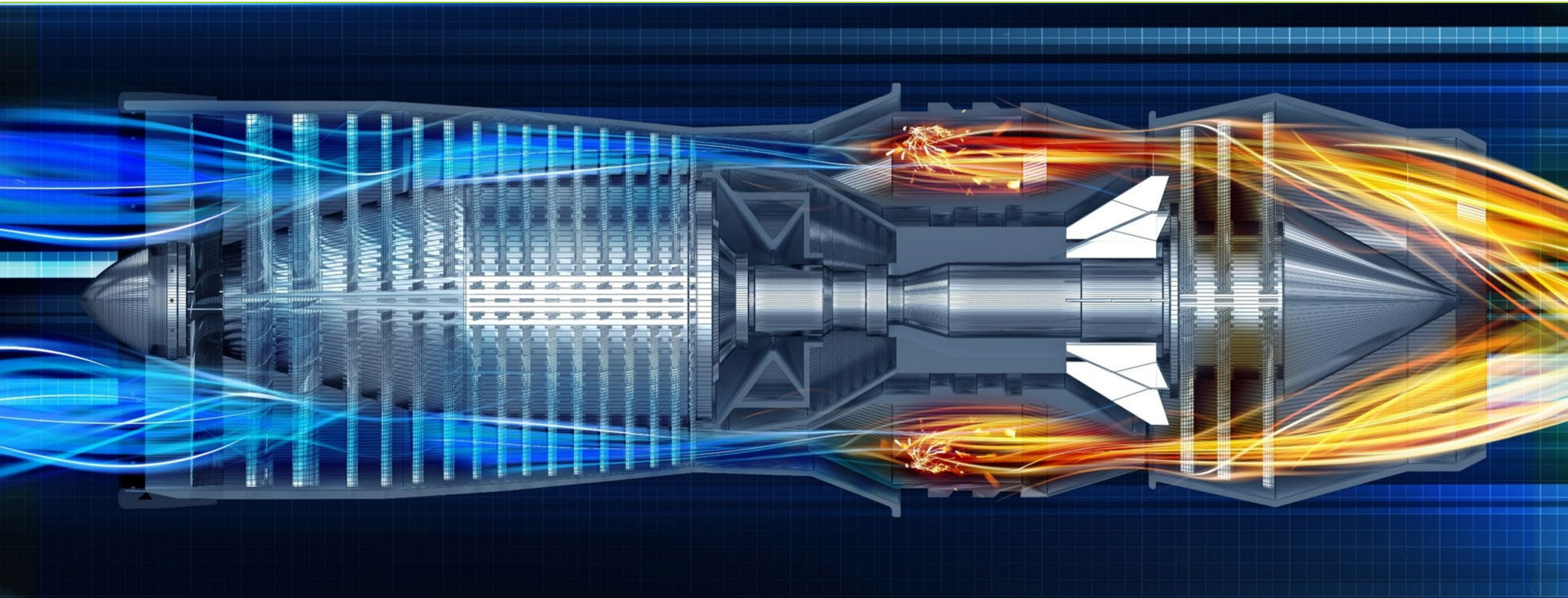
Hydrogen Combustion Research at NETL

Pete Strakey, NETL, September 2022



Hydrogen Combustion Capabilities at NETL

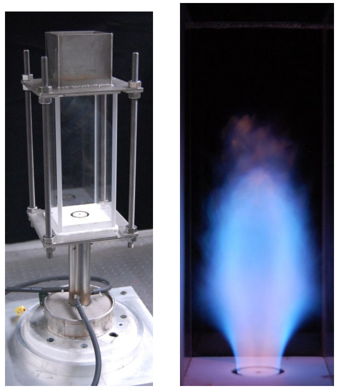
NATIONAL ENERGY TECHNOLOGY LABORATORY

Low and High Pressure Rigs, Diagnostics and CFD Modeling

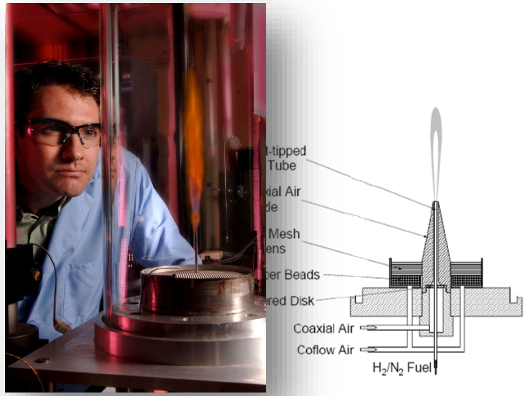
B-6 MGN Campus

SimVal Combustor

Bluff Body Burner



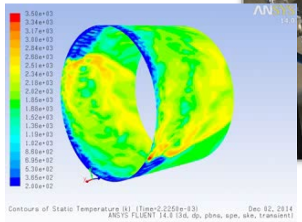
Diffusion Flame Burner



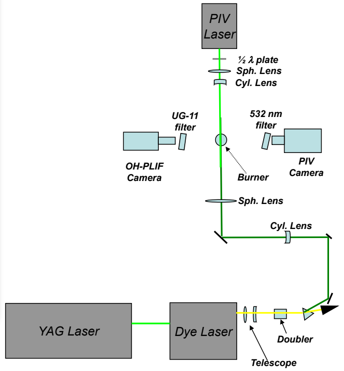
~ 200 SLPM, H2/CH4/CO

- High pressure combustion and heat transfer
- Preheated air up to 2 lb/sec @ 800°F
- Combustor pressures up to 20 atm
- Laser diagnostics / High speed imaging
- Gas sampling
- Natural Gas, LNG and Hydrogen up to 2 MW thermal output

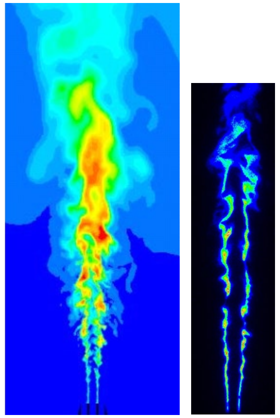
Cooled RDE Testing



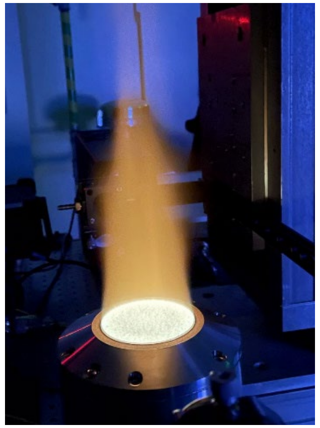
PLIF + PIV Setup



LES Simulation



NH3/H2 flame in NETL PGH FCL

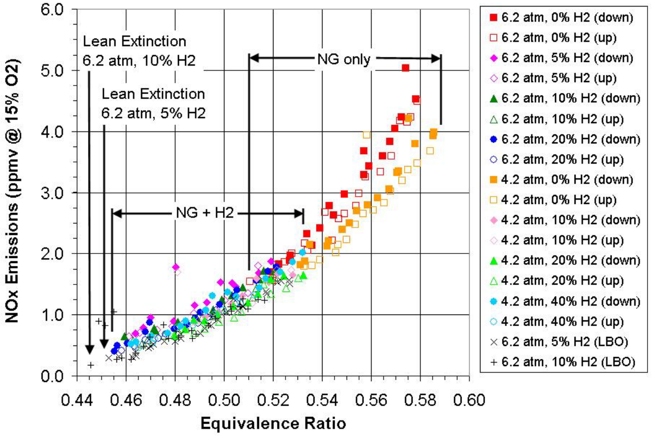


Premixed Hydrogen Combustion – Experiments and Model Validation

SimVal 20 atm Combustor

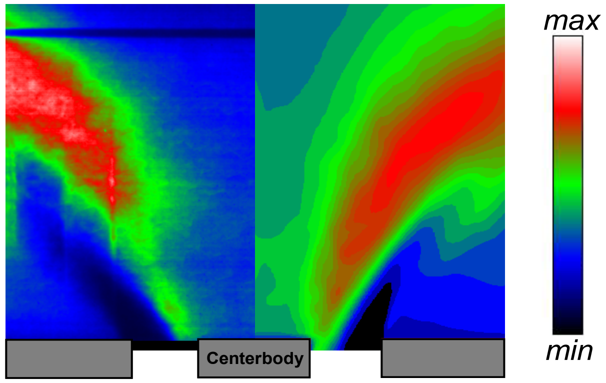
- Studied heat release distribution and NOx emissions with increasing H_2 content (up to 60%) at pressures up to 16 atm.
- OH-PLIF used to characterize heat release.
- Downstream bulk gas sampling for NOx.
- ANSYS Fluent LES with detailed chemistry used for model validation

NOx Emissions

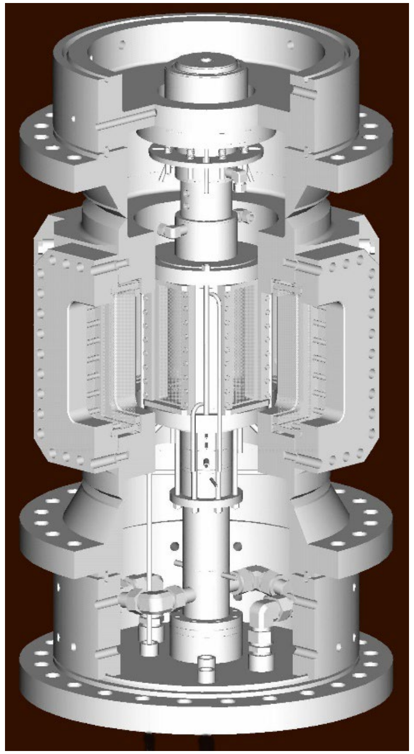


Average Fluorescence Intensity
Experiment

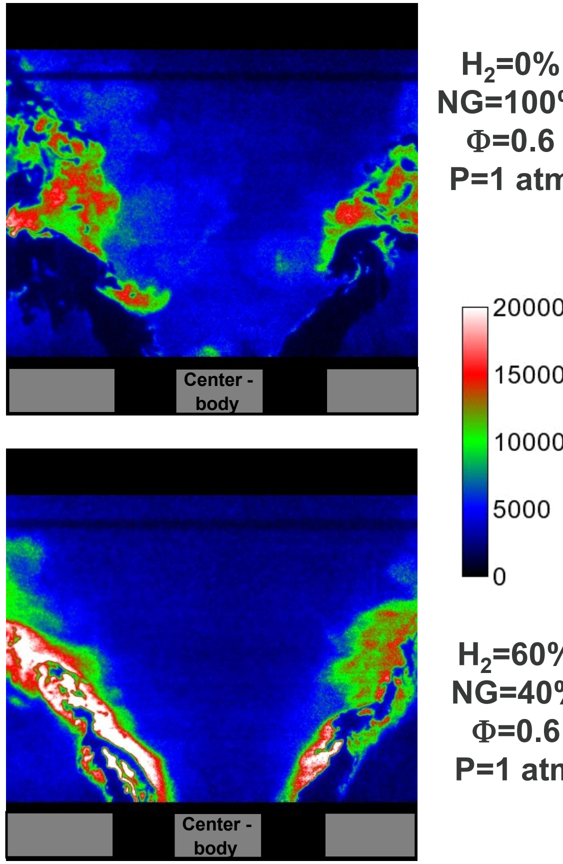
Average OH mole fraction
LES Simulation



SimVal Combustor



OH-PLIF Data



H_2=0%
NG=100%
Φ=0.6
P=1 atm

H_2=60%
NG=40%
Φ=0.6
P=1 atm

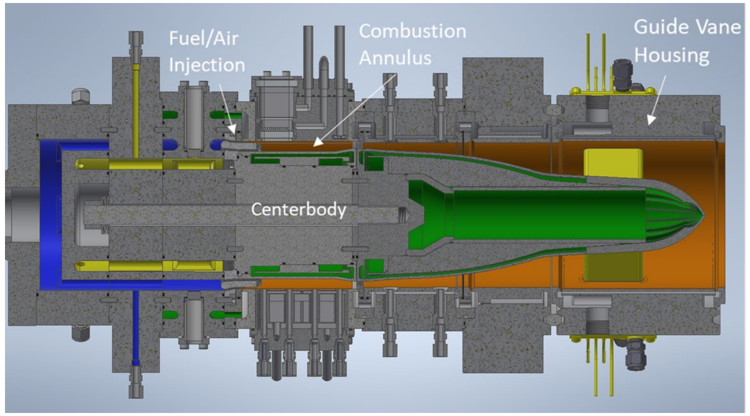
Pressure Gain Combustion – Rotating Detonation Engine
(collaboration with NASA and DoD)

NATIONAL ENERGY TECHNOLOGY LABORATORY

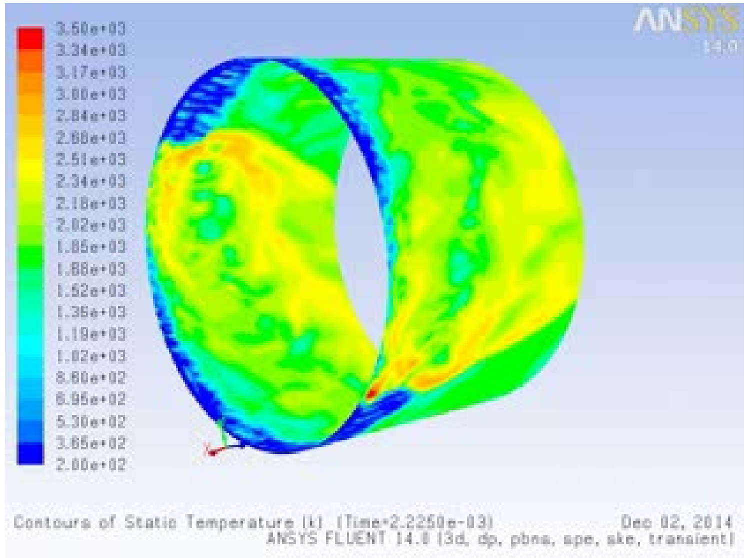
Motivation

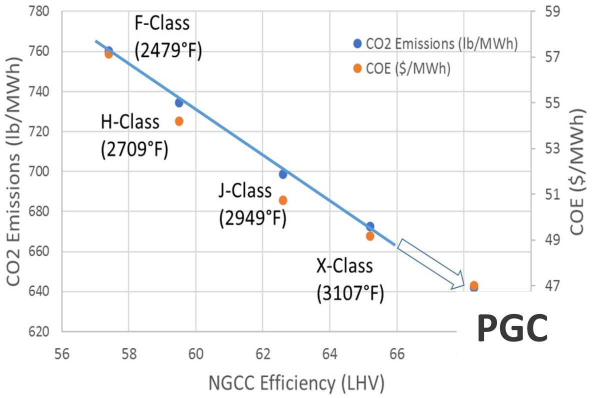
- Offers significant efficiency and COE benefit: Internal systems models suggest 4.9% increase in GT Efficiency (LHV) and 1.8% increase in Net Plant Efficiency (NGCC with H-Class RDE-GT Hybrid)
- Alternate and additive pathway to efficiency improvement
- Creates a new class of machine reducing COE

Water Cooled RDE Experiment

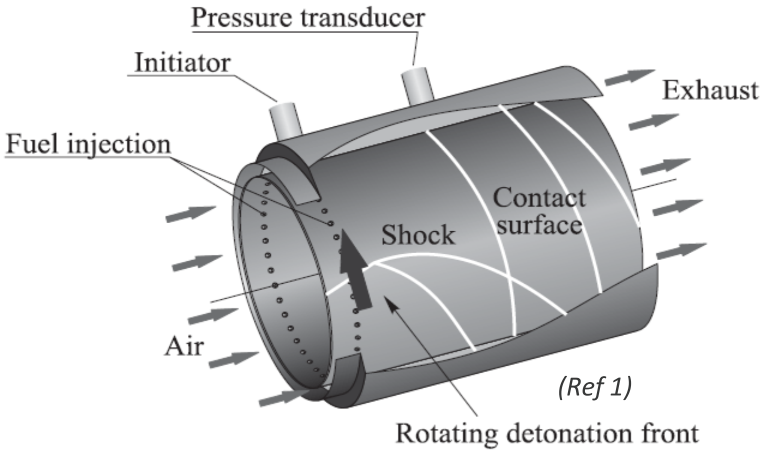


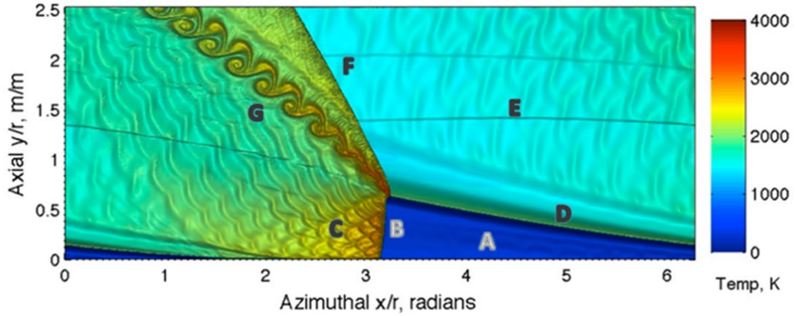
CFD model of H_2/Air RDE





RDE Combustor





Single wave combustion characteristics in an RDE.

A. Fresh Reactants
B. Detonation wave
C. Post-Detonation / Transverse Waves
D. Contact Surface (Def)
E. Product Expansion (Det, Det+Def)
F. Oblique Shock Wave
G. Shear Layer

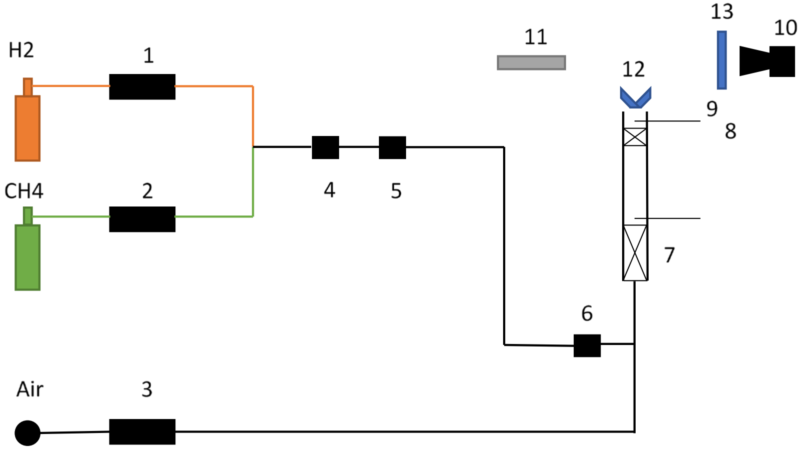
(Ref 2)

Flashback in Bench-Scale Low Swirl Burner

LES with H_2/CH_4 Fuel Blend

- Studying flashback in a Low Swirl Burner with hydrogen / methane fuel blends.
- Developing experimental data for model validation.
- Elucidating underlying physics.

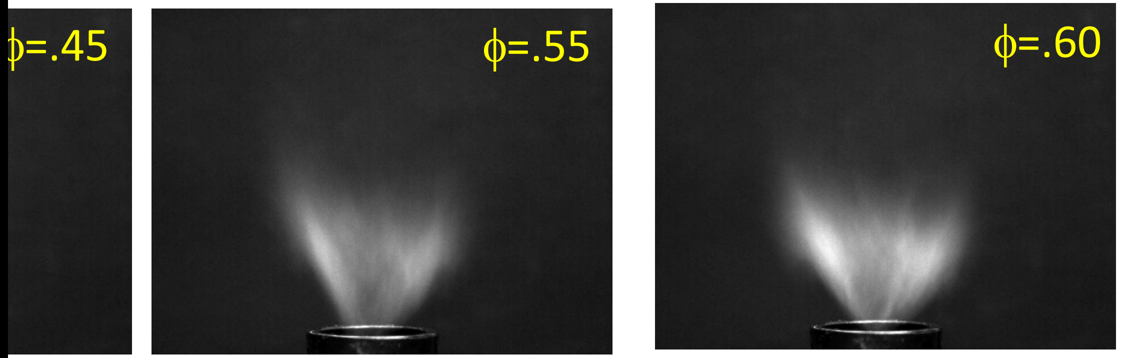
Swirler



LES, 11M Cells

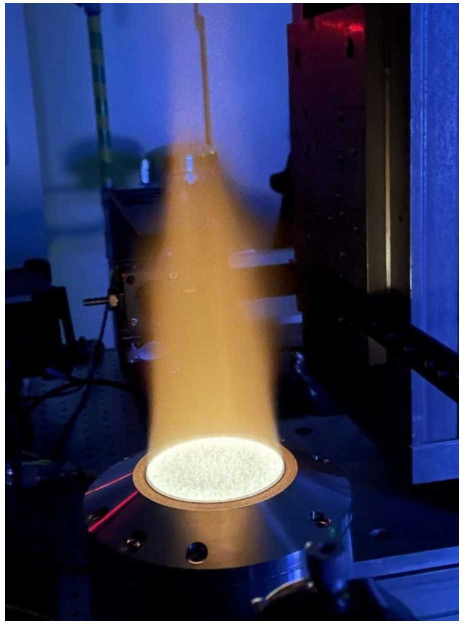
- 80% H_2 / 20% CH_4
- 2-step global mechanism

Flame Images: 80% H_2 / 20% CH_4



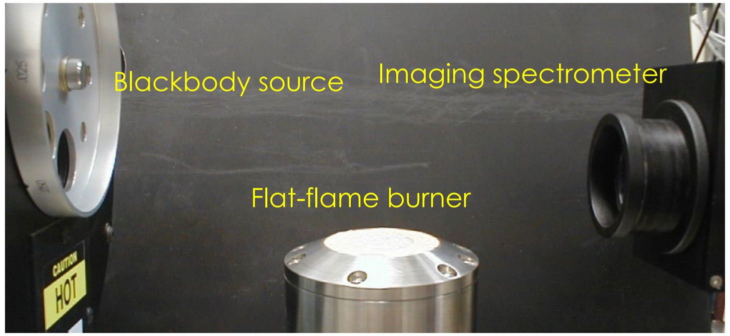
Ammonia Combustion

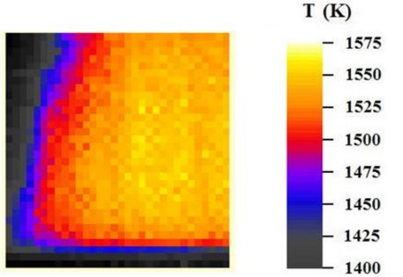
- **Attractive hydrogen carrier due to high volumetric energy density, low storage pressures**
- **<u>Challenge</u>: low flammability, propensity for high NOx/low comb. efficiency**
  - Kinetics differ greatly from HC (fuel-N)
  - New, optimized comb. strategies needed (ex. 2-stage rich-lean)
- **Requires improved fundamental understanding of kinetics and detailed/accurate model validation data**
- **Planned approach:**
  - Fundamental characterization of flames
  - Stability enhancement via partial reforming NH_3 to H_2
  - Modeling/CFD- NETL and Argonne National Lab

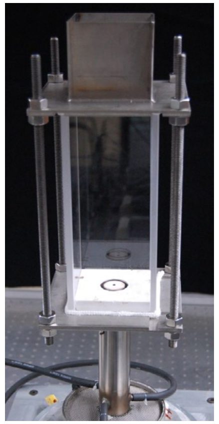


NH3/H2 flame in NETL PGH FCL

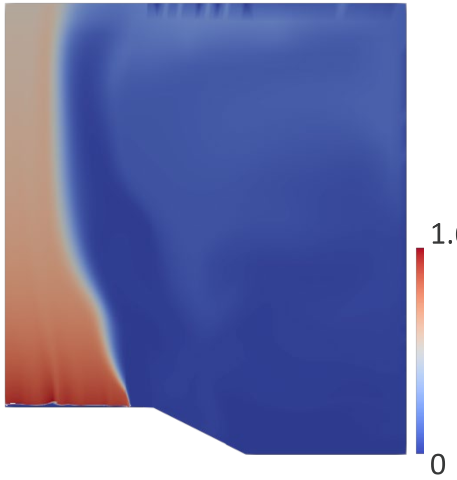
Imaging spectrometer for NH3/NOx in 1-5 μm







Example model gas turbine combustor from past CH_4/H_2 work at NETL



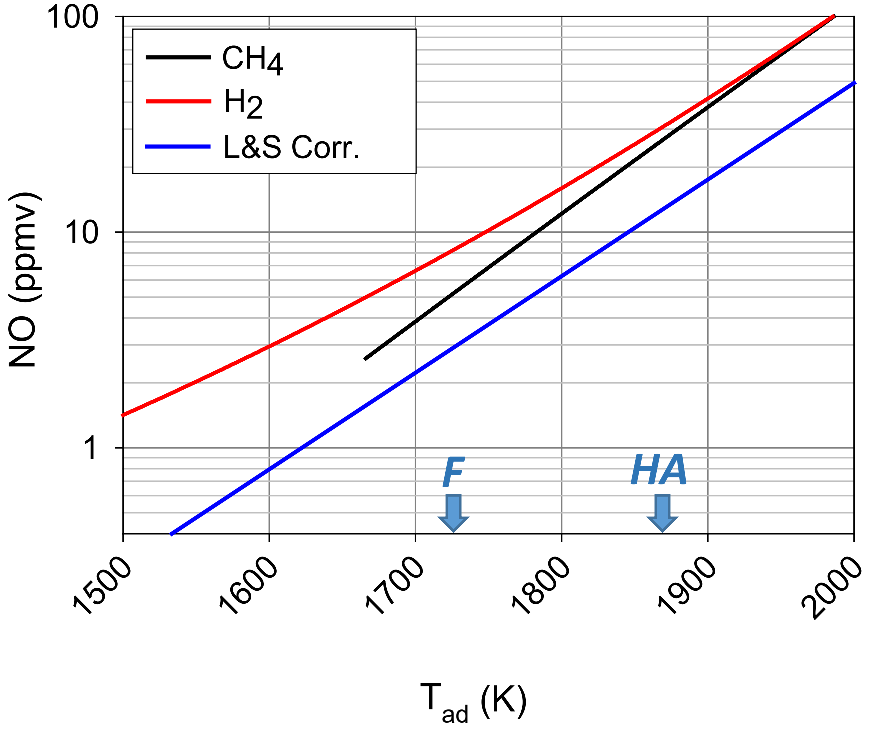
NO from OpenFOAM simulation of 50/50 H_2/NH_3 flame (Φ=1)

NOx Entitlement Estimation for H_2

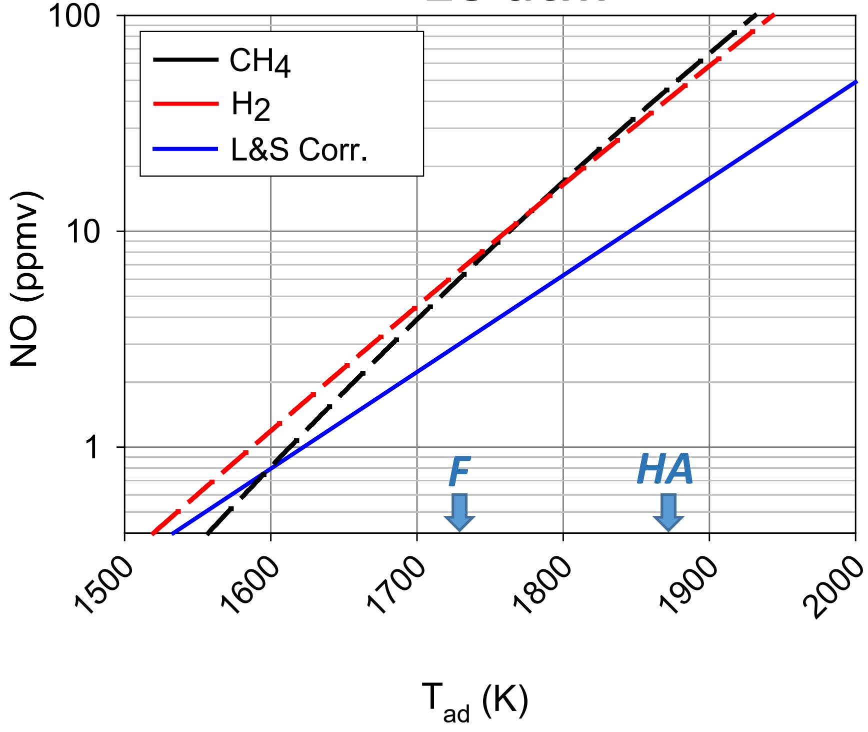
Cantera PSR/PFR Combination Used for NOx Estimates

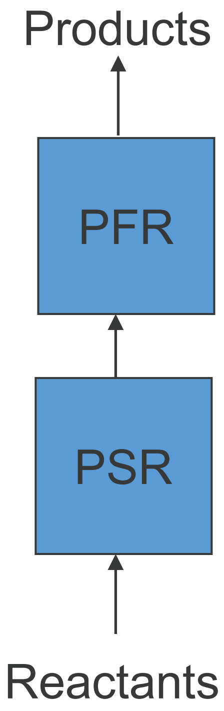
(Assumes perfect mixing)

4 atm



20 atm





NNH Route

(13) $N_2 + H \Leftrightarrow NNH$

(14) $NNH + O \Leftrightarrow NH + NO$

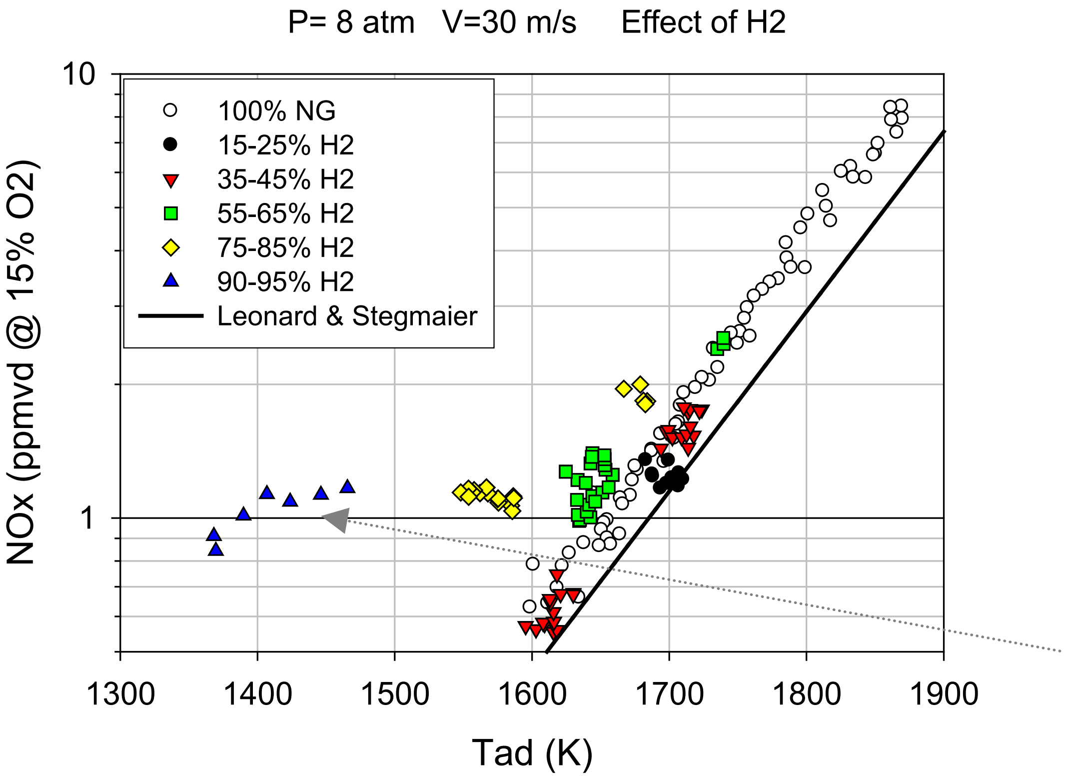
(15) $NNH + O \Leftrightarrow N_2O + H$

(16) $NNH + O \Leftrightarrow N_2 + OH$

- Slight increase in NO at 4 atm and lower temperatures for H_2 due to NNH route.
- Negligible difference at 20 atm for temperatures of interest.

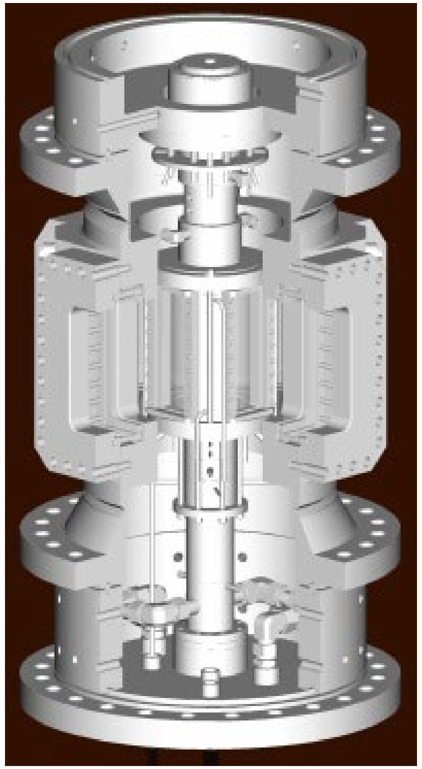
NOx Formation with a Low-Swirl Injector

Experimental Measurements in the NETL SimVal Rig



"Plateau" effect similar to PSR calculations (due to NNH route).

SimVal Combustor



- Similar results to high-swirl injector.
- NOx appears to be insensitive to H_2 at high temperatures (above 1700K) due to predominance of thermal route.

NOx Performance Standards

New EPA Standards based on flowrate / energy

- Emissions regulations based on dry ppm corrected to 15%O2 don't account for additional water produced with hydrogen combustion.
- [flowrate of NOx] / [J energy] is independent of O2/H2O in exhaust.

Example:
T=2000K
P=20 atm

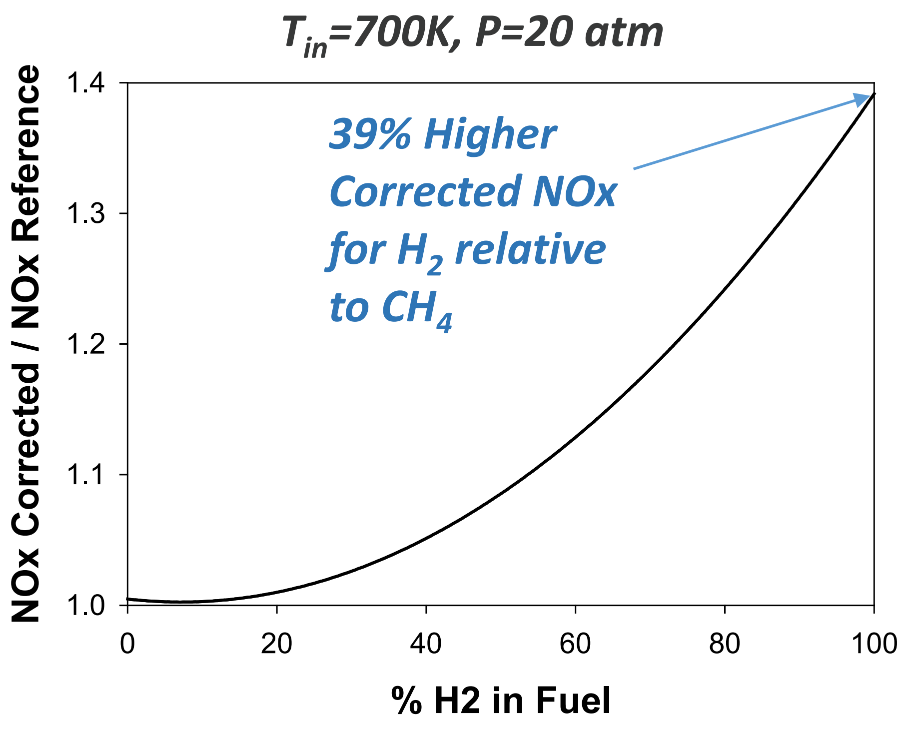
100% CH4	100% H2
$X_{O_2} = 0.073$	$X_{O_2} = 0.089$
$X_{H_2O} = 0.121$	$X_{H_2O} = 0.195$
$X_{CO_2} = 0.061$	

Conversion Equation:

$$^{*}NO_x@15\%O_2\ (ppmvd) = NO_x\left(\frac{.21-.15}{.21-\left[\frac{1}{1-X_{H_2O}}\right]X_{O_2}}\right)$$

Table 1: New Source Performance Standards for gas turbines[13]

EPA Category (Heat Input at baseload rating [HHV])	Market	Fuel	NO_x Limit @15% O_2 (based on gross energy output)
≥ 250 MW (850 MMBtu.hr)	Both	Natural Gas	15 ppm or 54 ng/J (0.43 lb/MW-hr)
		Other Fuels	42 ppm or 160 ng/J (1.3 lb/MW-hr)



* https://asmedigitalcollection.asme.org/gasturbinespower/article/144/9/091003/1143043