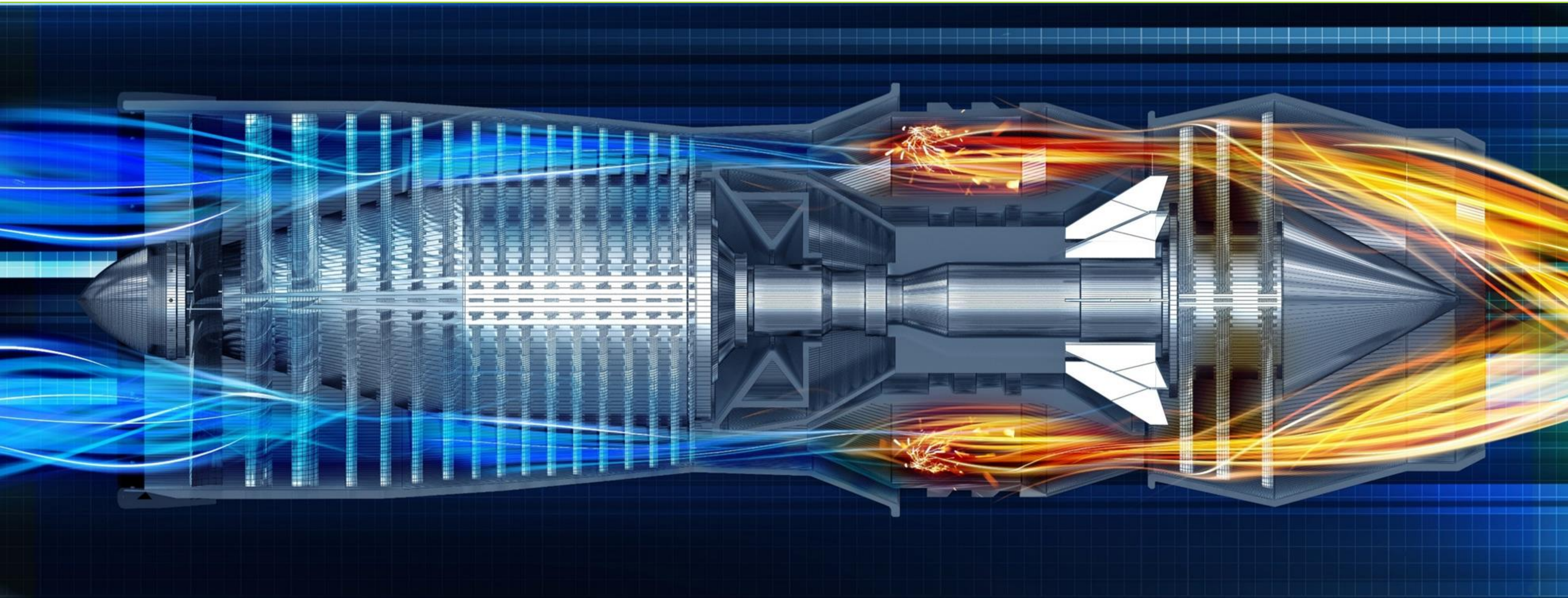
Hydrogen Combustion Research at NETL

Pete Strakey, NETL, September 2022



Hydrogen Combustion Capabilities at NETL

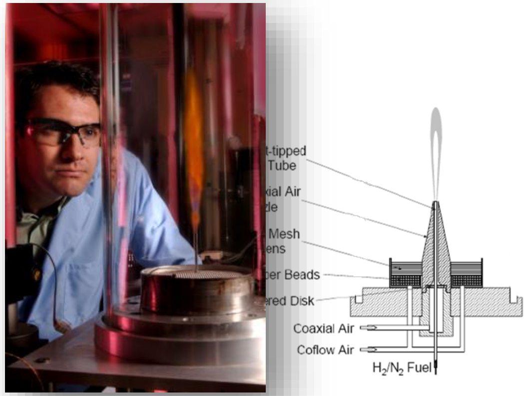
Low and High Pressure Rigs, Diagnostics and CFD Modeling

B-6 MGN Campus

SimVal Combustor

Bluff Body Burner

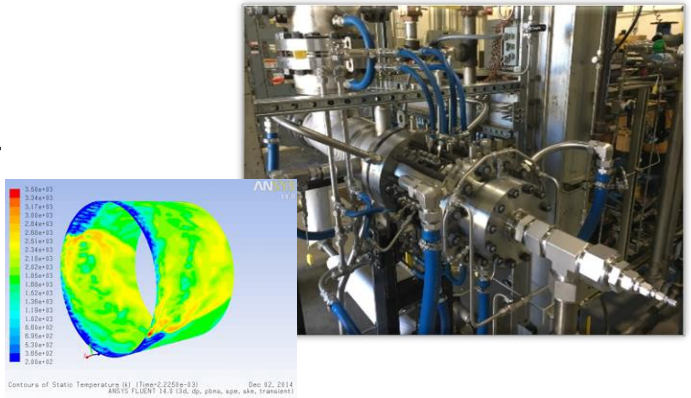
Diffusion Flame Burner



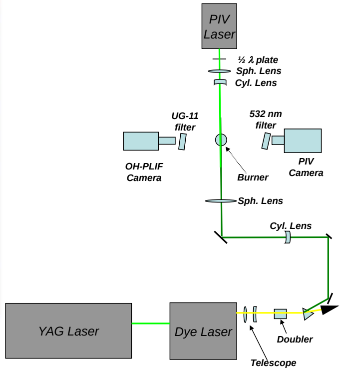
~ 200 SLPM, H2/CH4/CO

- 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

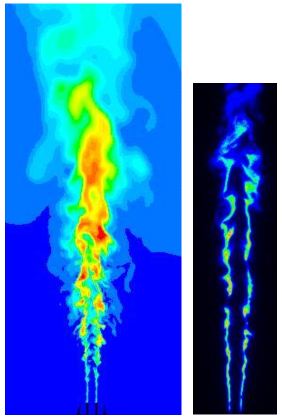
Cooled RDE Testing



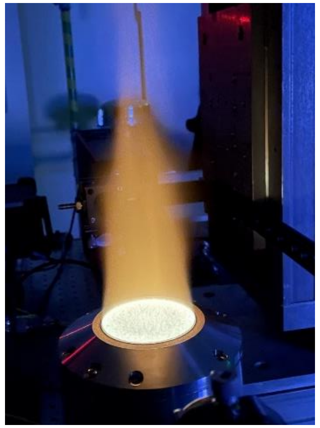
PLIF + PIV Setup



LES Simulation



NH3/H2 flame in NETL PGH FCL

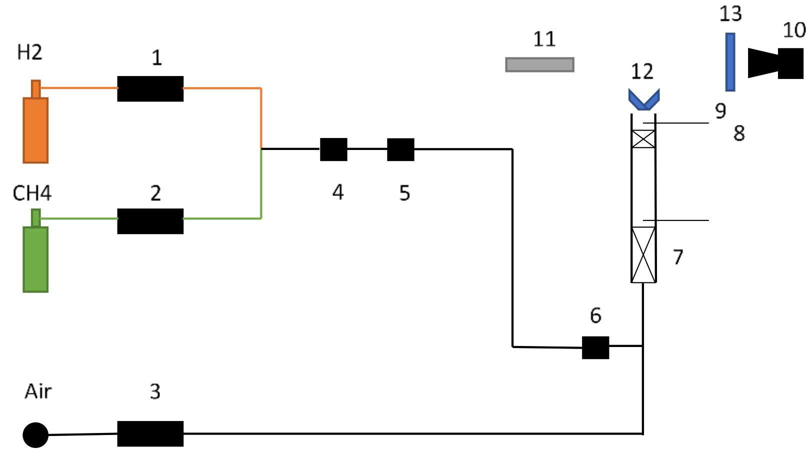


Flashback in Bench-Scale Low Swirl Burner

LES with H_2/CH_4 Fuel Blend

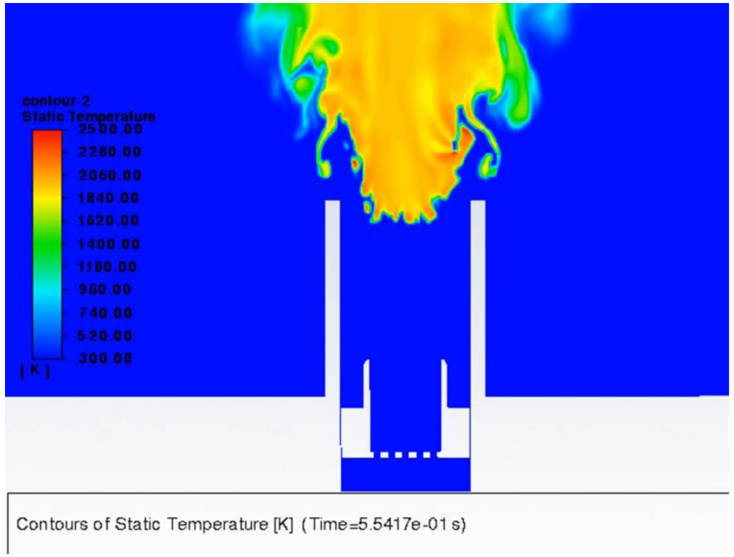
- Studying flashback in a Low Swirl Burner with hydrogen / methane fuel blends.
- Developing experimental data for model validation.
- Elucidating underlying physics.

Swirler

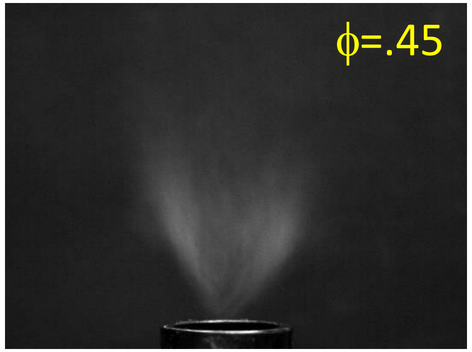


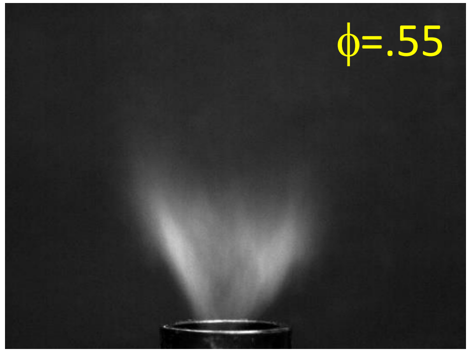
LES, 11M Cells

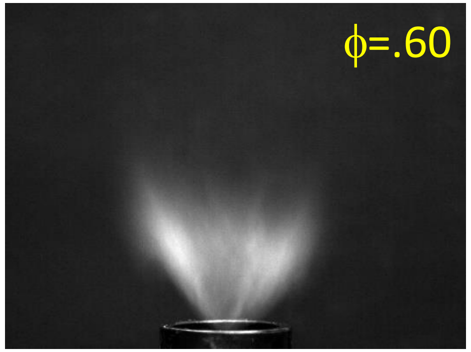
- 80% H_2 / 20% CH_4
- 2-step global mechanism



Flame Images: 80% H_2 / 20% CH_4



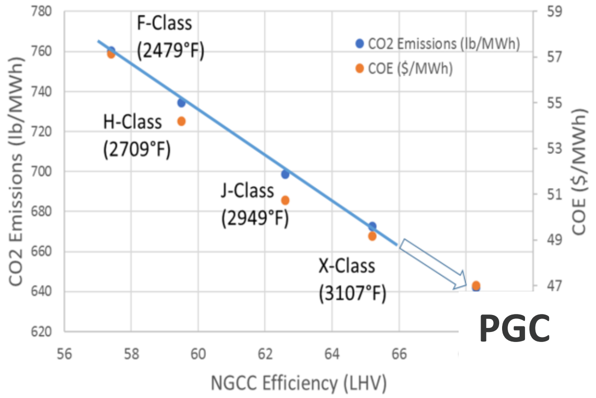




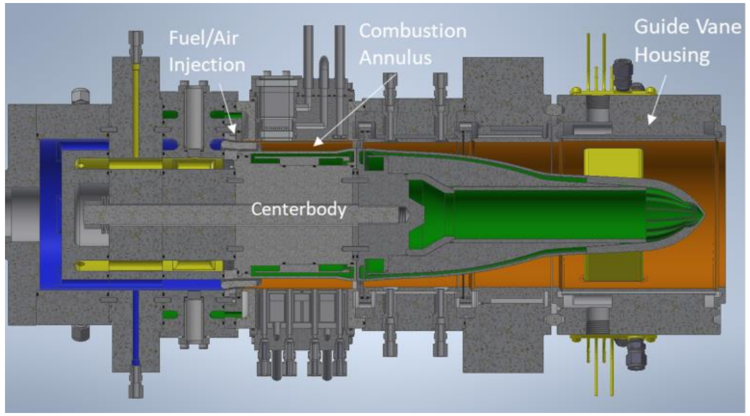
Pressure Gain Combustion – Rotating Detonation Engine
(collaboration with NASA and DoD)

Motivation

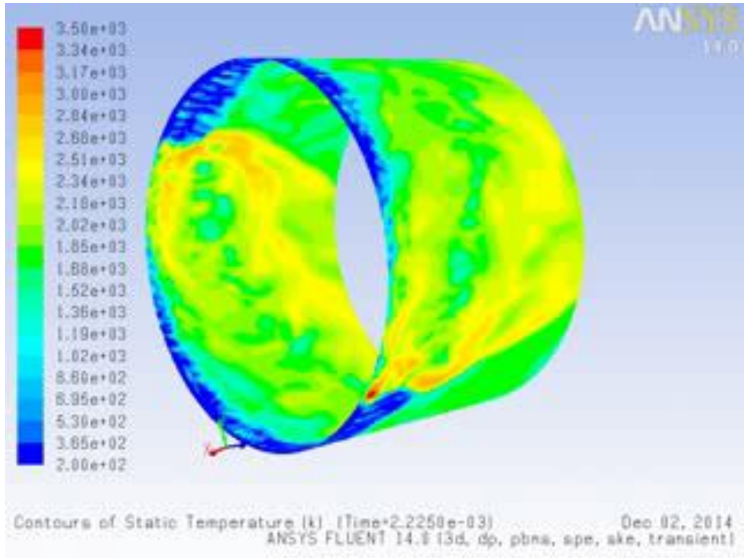
- Offers significant efficiency and COE benefit: Internal systems models suggest 4.9% increase in GT Efficiency (LHV) and 1.8% increase in Net Plant Efficiency (NGCC with H-Class RDE-GT Hybrid)
- Alternate and additive pathway to efficiency improvement
- Creates a new class of machine reducing COE



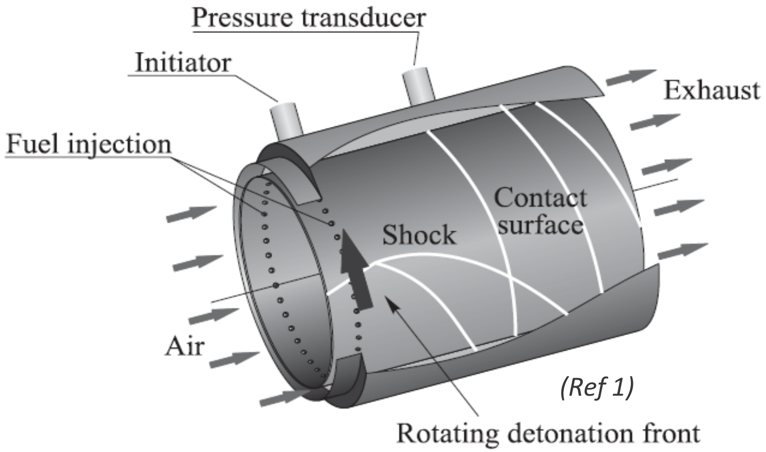
Water Cooled RDE Experiment

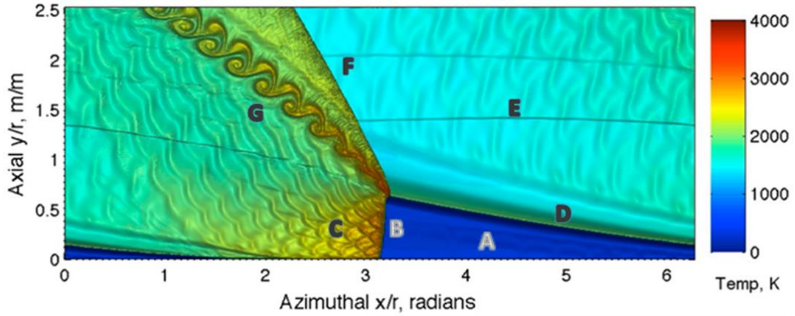


CFD model of H_2/Air RDE



RDE Combustor





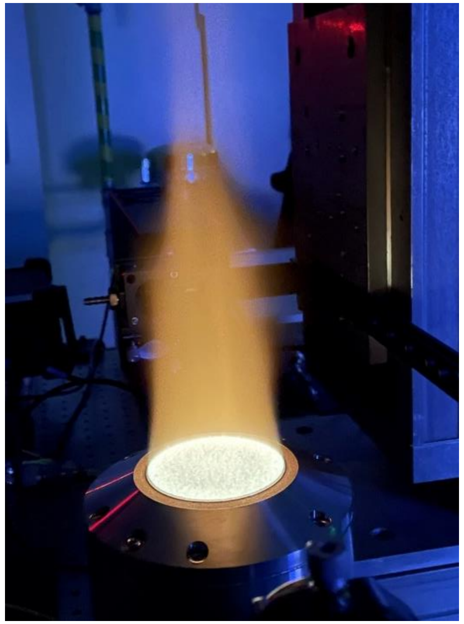
Single wave combustion characteristics in an RDE.

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)

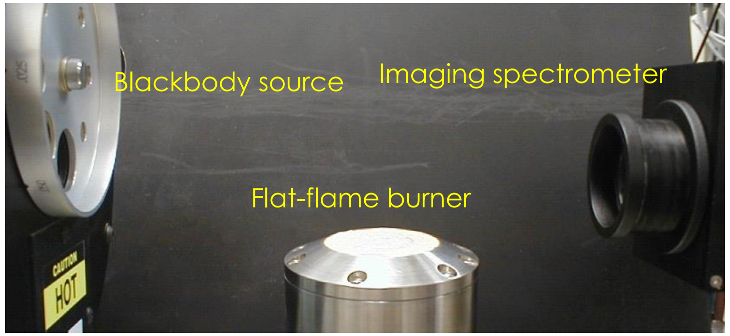
Ammonia Combustion

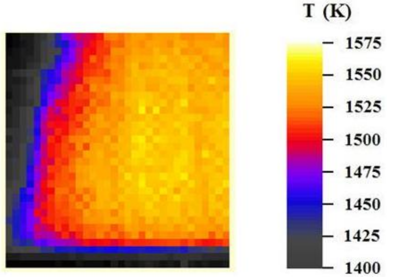
- **Attractive hydrogen carrier due to high volumetric energy density, low storage pressures**
- **<u>Challenge</u>: low flammability, propensity for high NOx/low comb. efficiency**
  - Kinetics differ greatly from HC (fuel-N)
  - New, optimized comb. strategies needed (ex. 2-stage rich-lean)
- **Requires 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



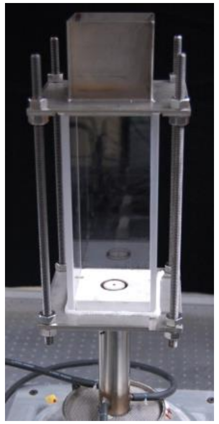
NH3/H2 flame in NETL PGH FCL

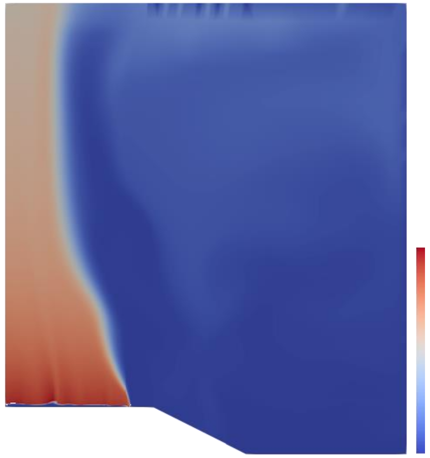
Imaging spectrometer for NH3/NOx in 1-5 μm





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

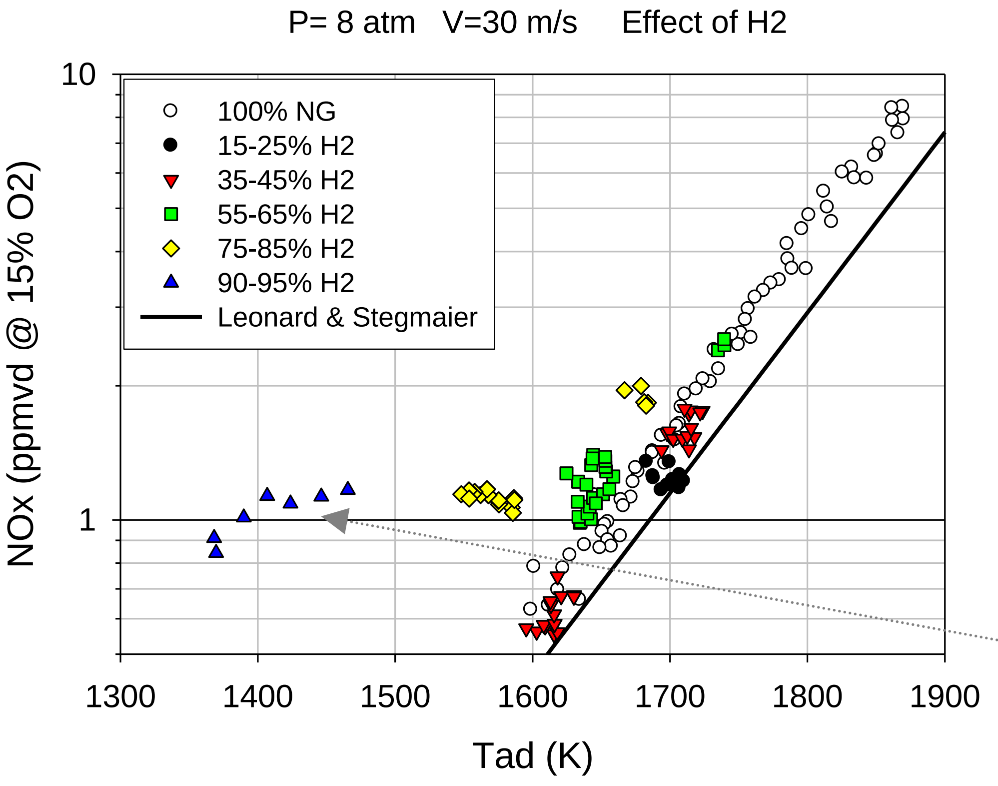




NO from OpenFOAM simulation of 50/50 H_2/NH_3 flame (Φ=1)

NOx Formation with a Low-Swirl Injector

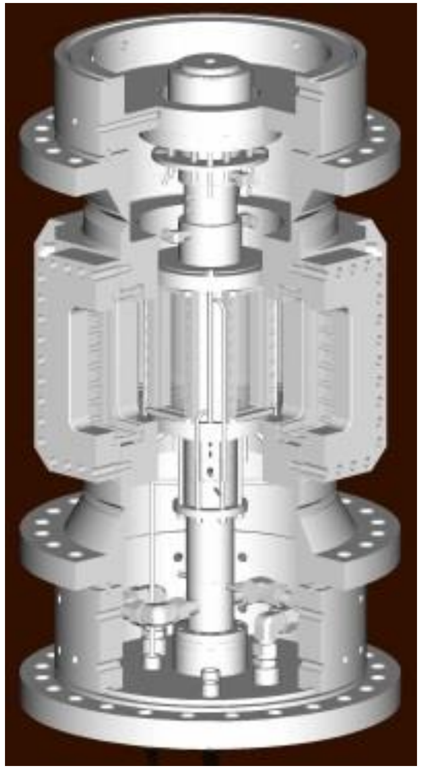
Experimental Measurements in the NETL SimVal Rig



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

LSI

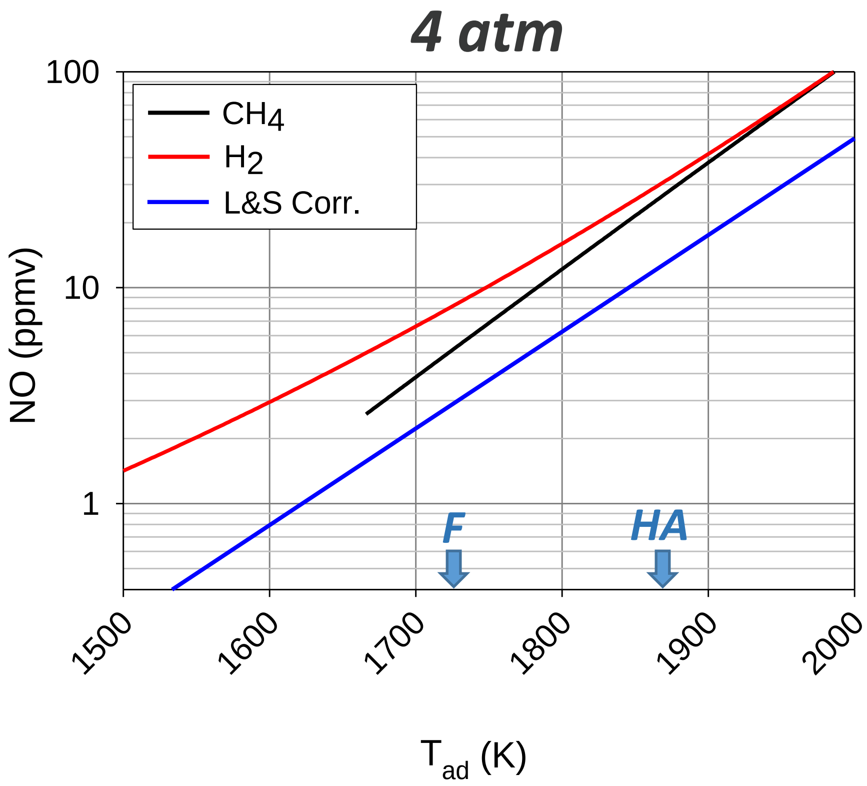
SimVal Combustor

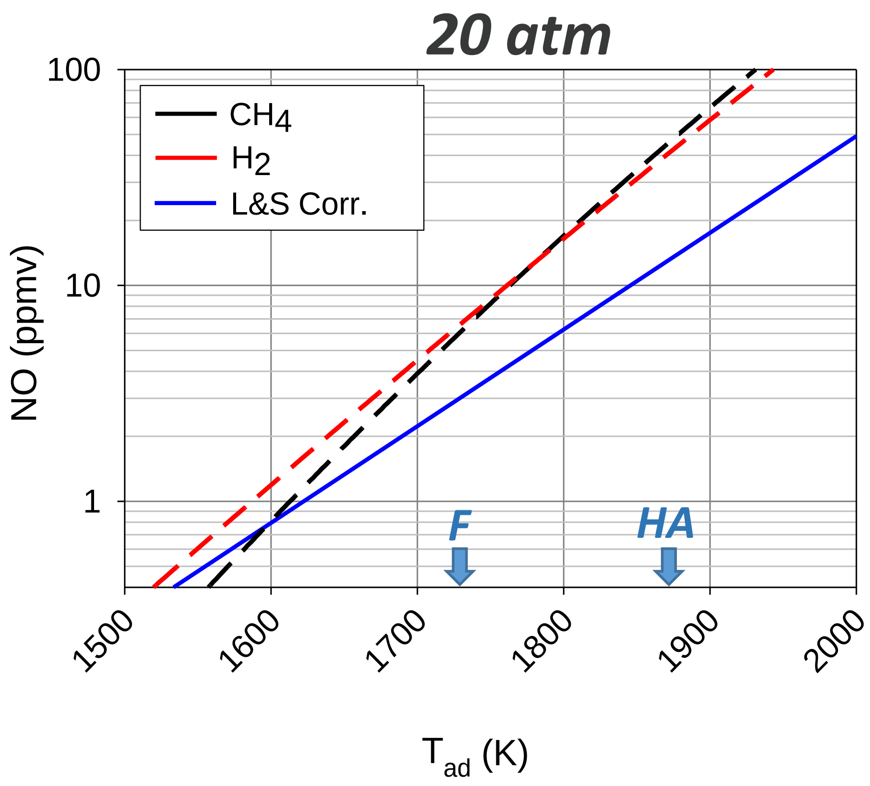


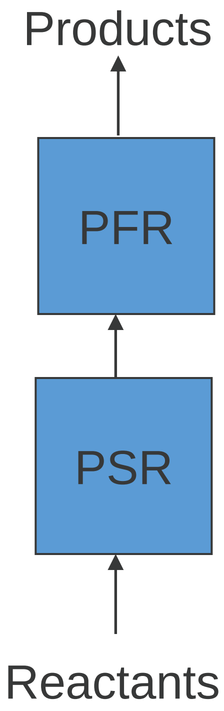
- Similar results to high-swirl injector.
- NOx appears to be insensitive to H_2 at high temperatures (above 1700K) due to predominance of thermal route.

NOx Entitlement Estimation for H_2

Cantera PSR/PFR Combination Used for NOx Estimates (Assumes perfect mixing)







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 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

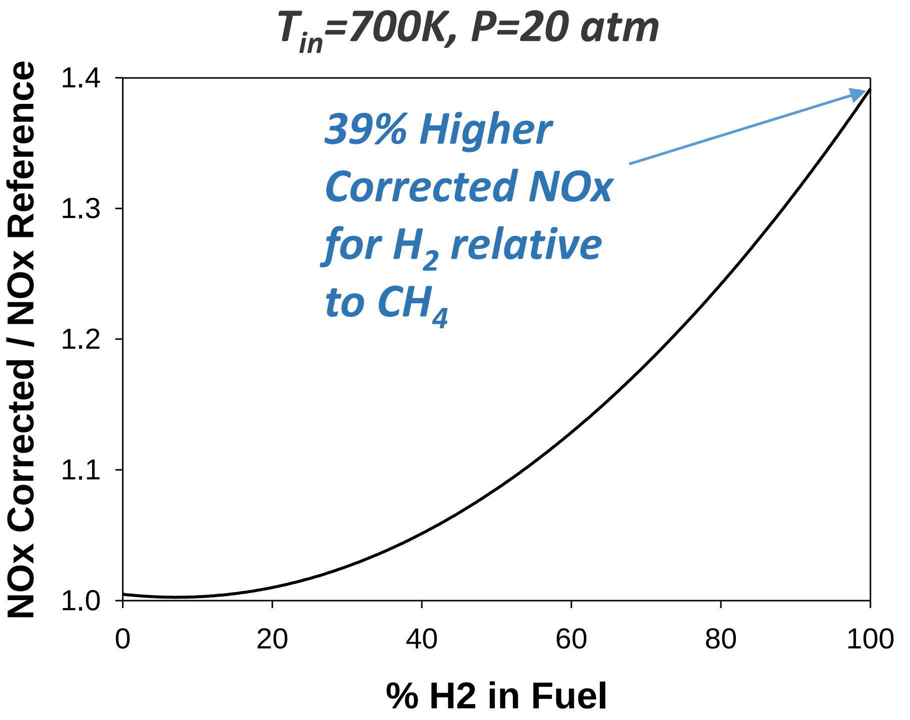
100% CH4	100% H2
$X_{O_2} = 0.073$	$X_{O_2} = 0.089$
$X_{H_2O} = 0.121$	$X_{H_2O} = 0.195$
$X_{CO_2} = 0.061$	

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	NOx Limit @15% O2 (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)



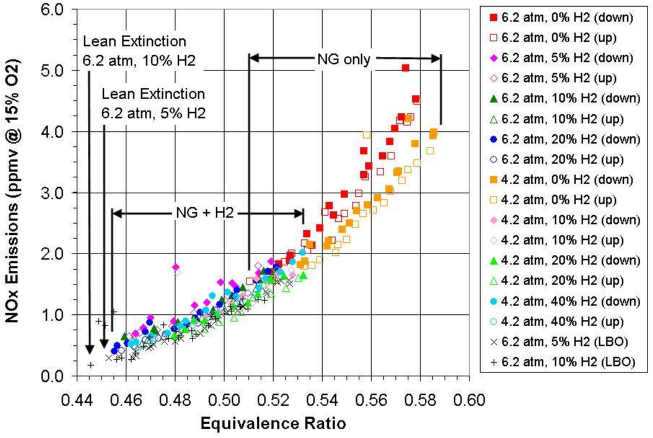
* https://asmedigitalcollection.asme.org/gasturbinespower/article/144/9/091003/1143043

Premixed Hydrogen Combustion – Experiments and Model Validation

SimVal 20 atm Combustor

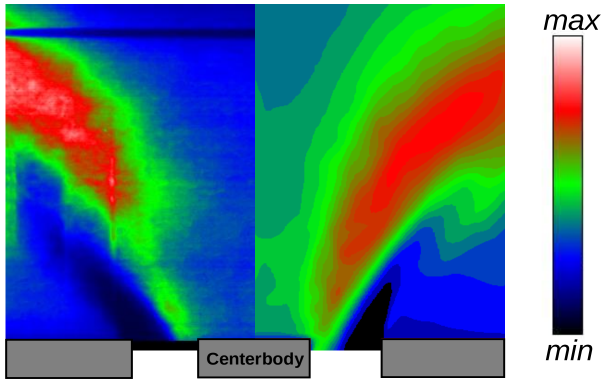
- Studied heat release distribution and NOx emissions with increasing H_2 content (up to 60%) at pressures up to 16 atm.
- OH-PLIF used to characterize heat release.
- Downstream bulk gas sampling for NOx.
- ANSYS Fluent LES with detailed chemistry used for model validation

NOx Emissions

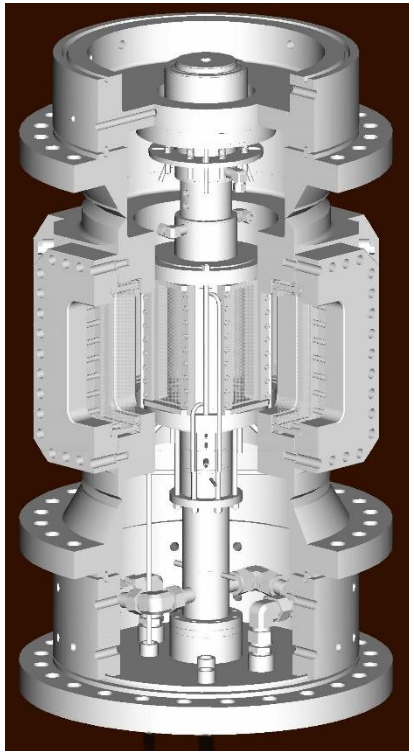


Average Fluorescence Intensity | *Average OH mole fraction*

Experiment | LES Simulation



SimVal Combustor



OH-PLIF Data