Gas Turbine Fuel Systems Division

Micro-Mixing Lean Premix System for Ultra-Low Emission Hydrogen/Syngas Combustion

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Outline

- Introduction
  - Project Overview; Research Objectives and Approach
- Micro-Mixing Cup Development
  - 1st Generation Micro-Mixing Cup – Radial Inflow Configuration
  - 2nd Generation Micro-Mixing Cup – Mixed Axial/Radial Inflow Configuration
  - Multi-cup Module
- Full-Scale 1.3 MW injector
  - Atmospheric tests (fuel-air mixing, flame imaging, emissions)
  - High-pressure combustion tests
- Summary and Conclusions

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Micro-Mixing Lean Premix System for Ultra-Low NOx Emission Hydrogen/Syngas Combustion

Research Objectives

- Develop new Lean Premix concepts for H2/Syngas combustion for Gas Turbine Engines in the power range 1- 100 MW.
- 3 ppm NOx emissions operating on H2/Syngas fuels at representative full-scale engine conditions.

Approach

- Scalable Macrolamination technology
- Single mixing cup as building block

Benefits

- Fast and efficient micro-scale mixing
- Fuel flexibility
- Scalable to all engine sizes

Project Partners

- Parker Hannifin
- Univ. of California Irvine
- Engine OEM

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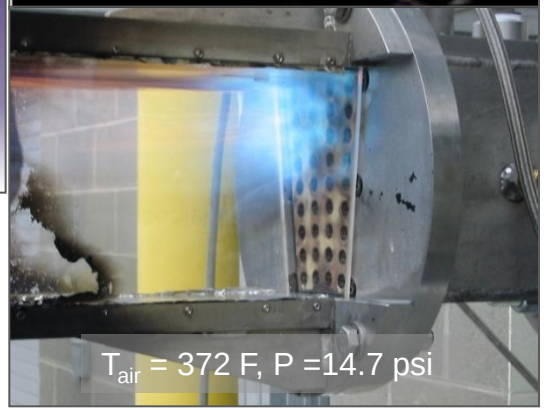
Background: Macrolamination Integrated Dome Technology (I-Dome)

- LDI Multipoint Injection.
  - 80 to 90 % of combustor air is admitted through dome.
  - Good atomization
  - Rapid mixing
- Short flames, reduced liner cooling air, good pattern factor
- Effective staging
- No auto-ignition or flashback problems
  - Tailored swirl number
  - Short mixing length

Flame length is less than 1 in



T_{air} = 372 F, P =14.7 psi

Tested at up to 27 atm on liquid fuel. NOx emissions 17% of 1996 ICAO Standard

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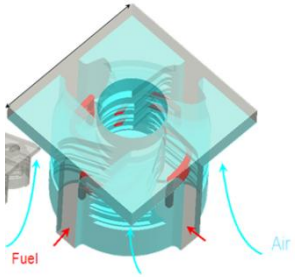
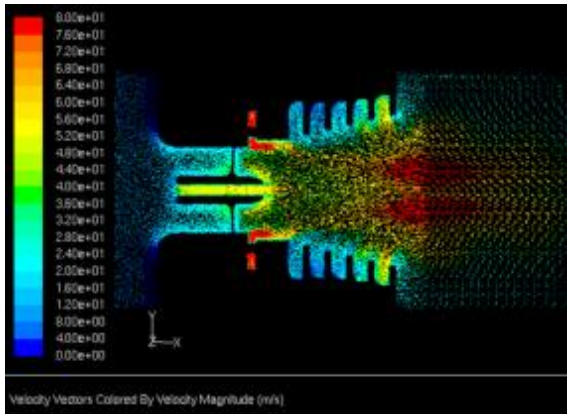
Micro-Mixing Lean Premix System for Ultra-Low NOx Emission Hydrogen/Syngas Combustion

Single Cup Module

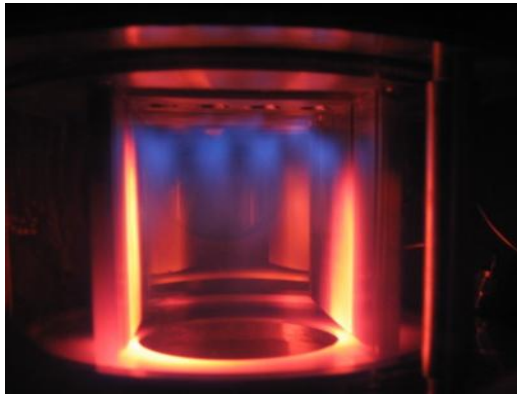
1st Generation: Radial Air Flow



2nd Generation Radial/Axial Air Flow



Multi-cup Module



1MWth Full Scale Injector

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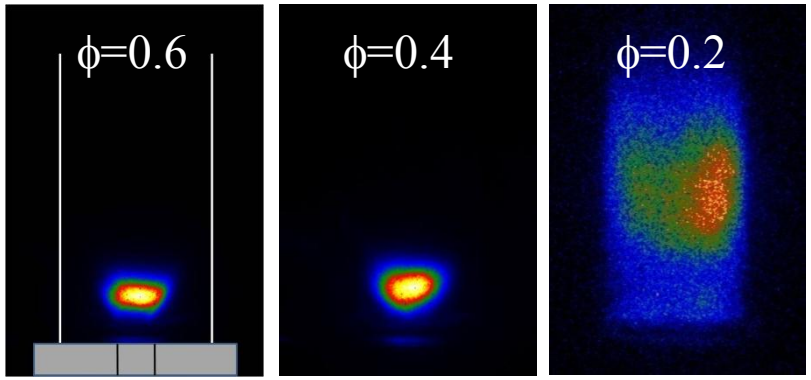
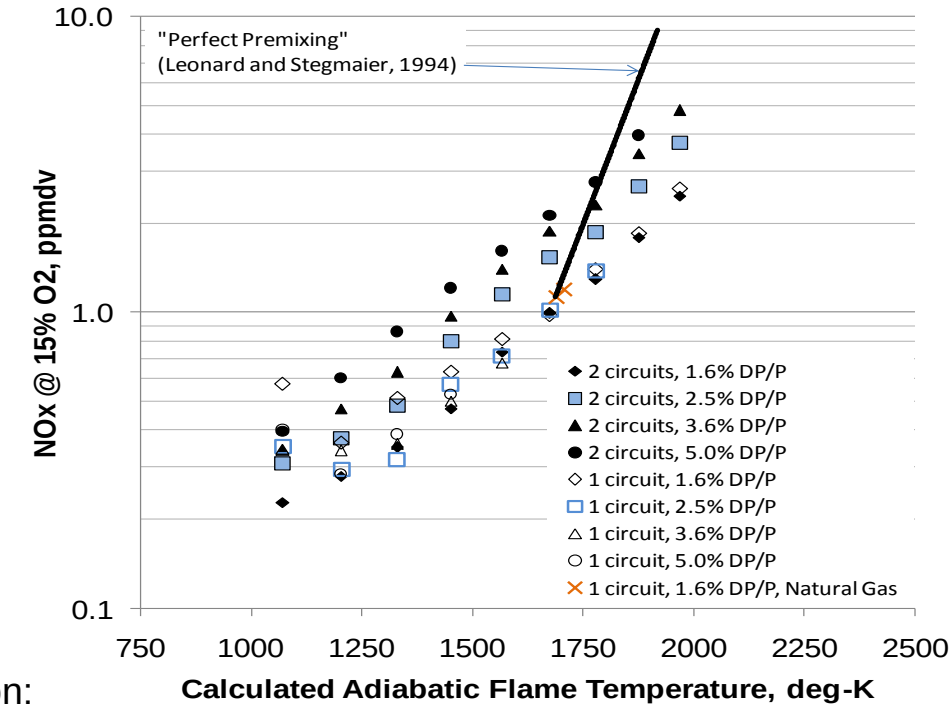
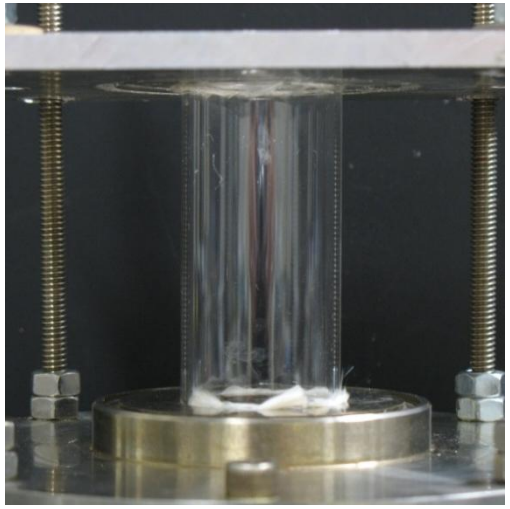
Micro-Mixing Cups – Radial Air Inflow Design Atmospheric Testing Results

- Hydrogen & Natural Gas

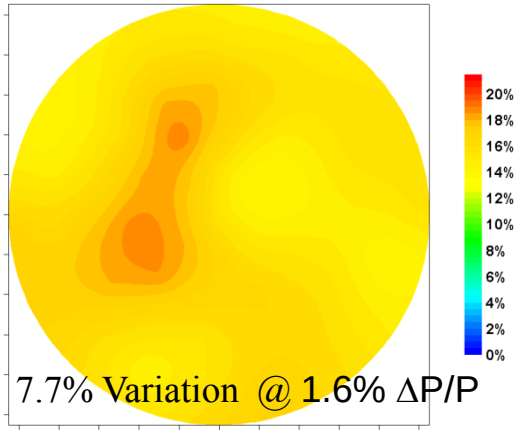


OH* Chemiluminescence – H2 flames





H_2 Volume Fraction:



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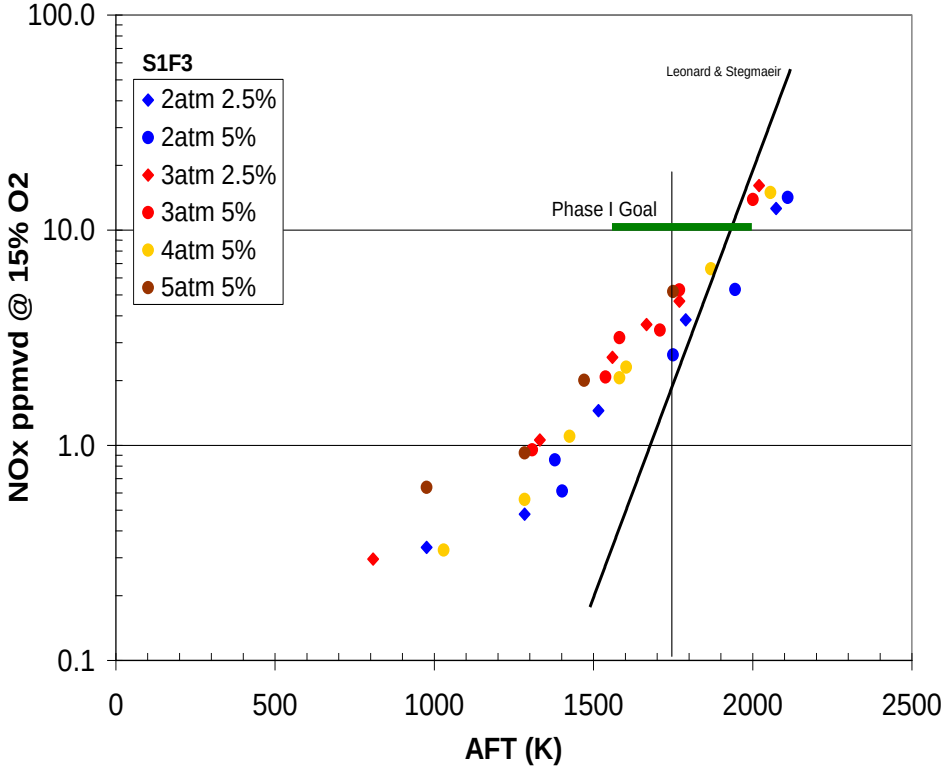
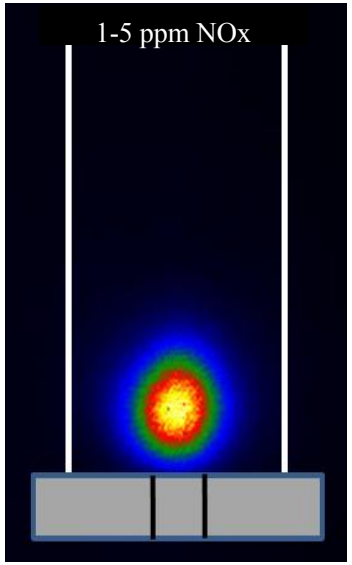
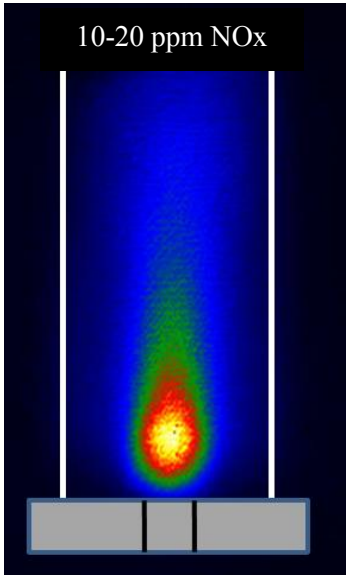
Micro-Mixing Cups – Radial Air Inflow Design High Pressure Testing Results

- S1F3 – 100% Hydrogen





S1F3, 2 atm, 1750 deg-K
5% ΔP/P



S1F3, 4 atm, 1675 deg-K
5% ΔP/P

- At P > 5 atm, flame ingress was observed for AFTs of interest
- No hardware distress after 30 min of operation in ingressed mode

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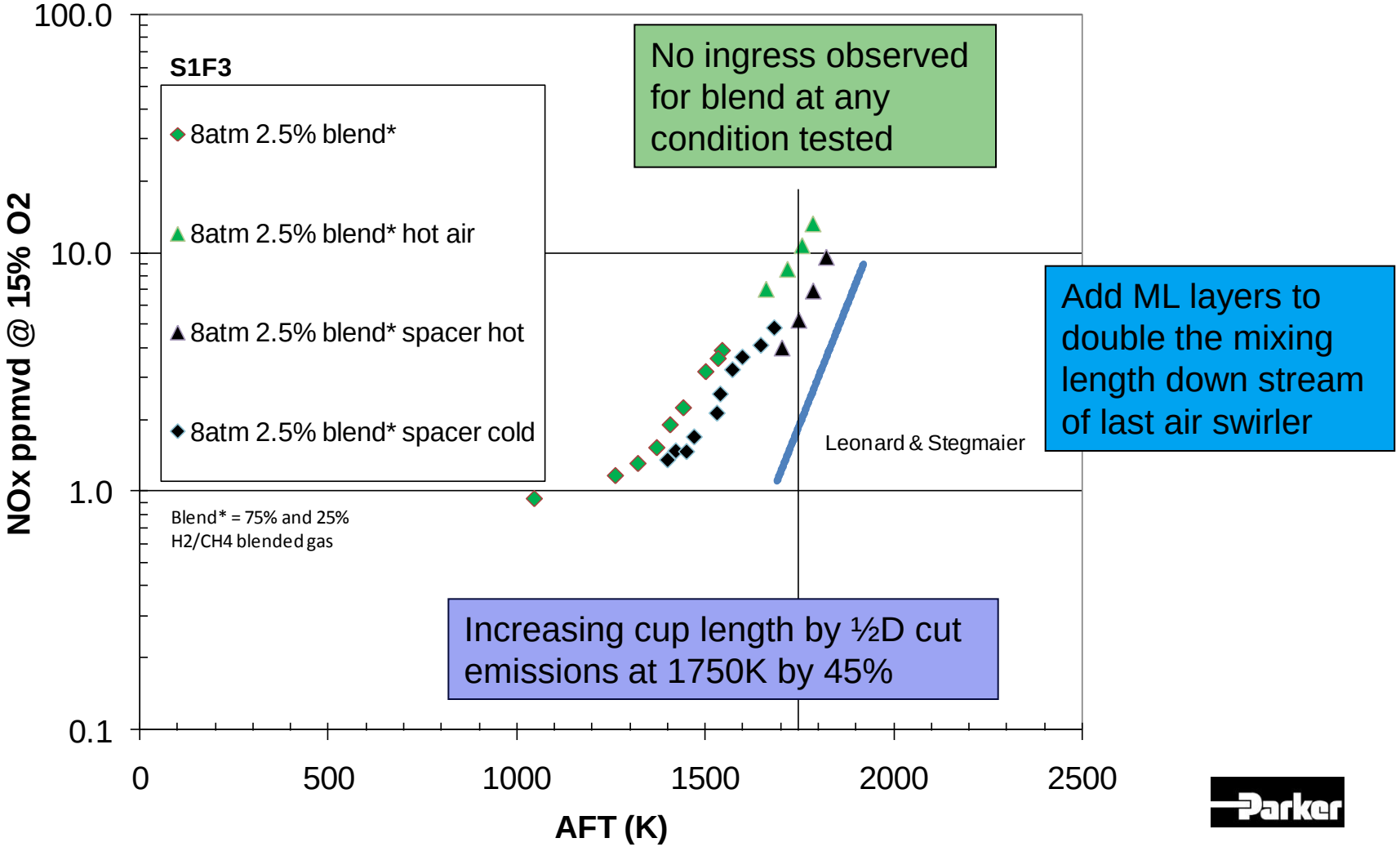
Micro-Mixing Cups – Radial Air Inflow Design Emissions and Operability of Fuel Blends

- High-Pressure Test Results



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Micro-Mixing Cups – Radial Air Inflow Design Summary

- Excellent Single Cup Emissions on 100% Hydrogen Fuel
  - <2 ppm NOx (@ 15% O_2) @ 1750 K for 1 atm
  - <5.5 ppm NOx (@ 15% O_2) @1750 K up to 5 atm
- Single Cup Robustness on 100% Hydrogen Fuel
  - Flame ingress above 5.5 atm
  - No mechanical distress when operating with ingressed flame, BL ingress mechanism identified
- Single-Cup Operation on fuel mixture (75% H2, 25% Methane)
  - About 5 ppm NOx (@ 15% O2) at 8-atm and 1750 K
  - No flame ingress observed at any conditions tested.
  - Ability to impact emissions with mixing length demonstrated

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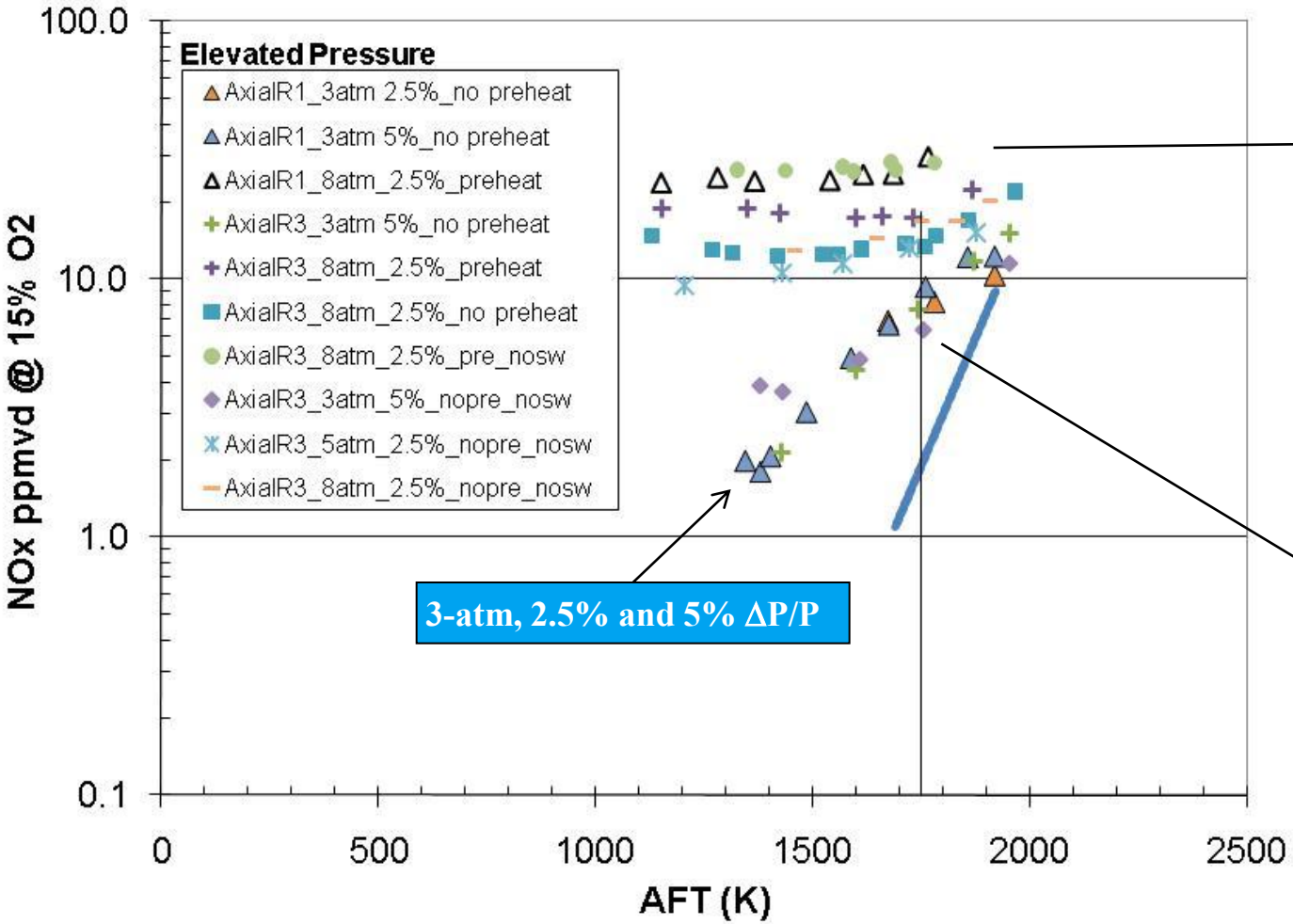
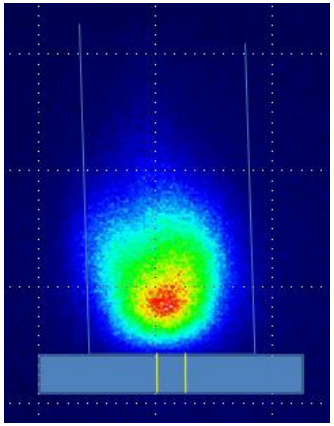
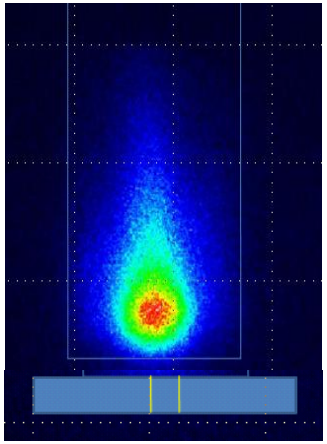
Micro-Mixing Cup – Radial/Axial Airflow Design Emissions using 100% Hydrogen

- 3-atm to 8-atm Combustion Tests





8atm



3atm

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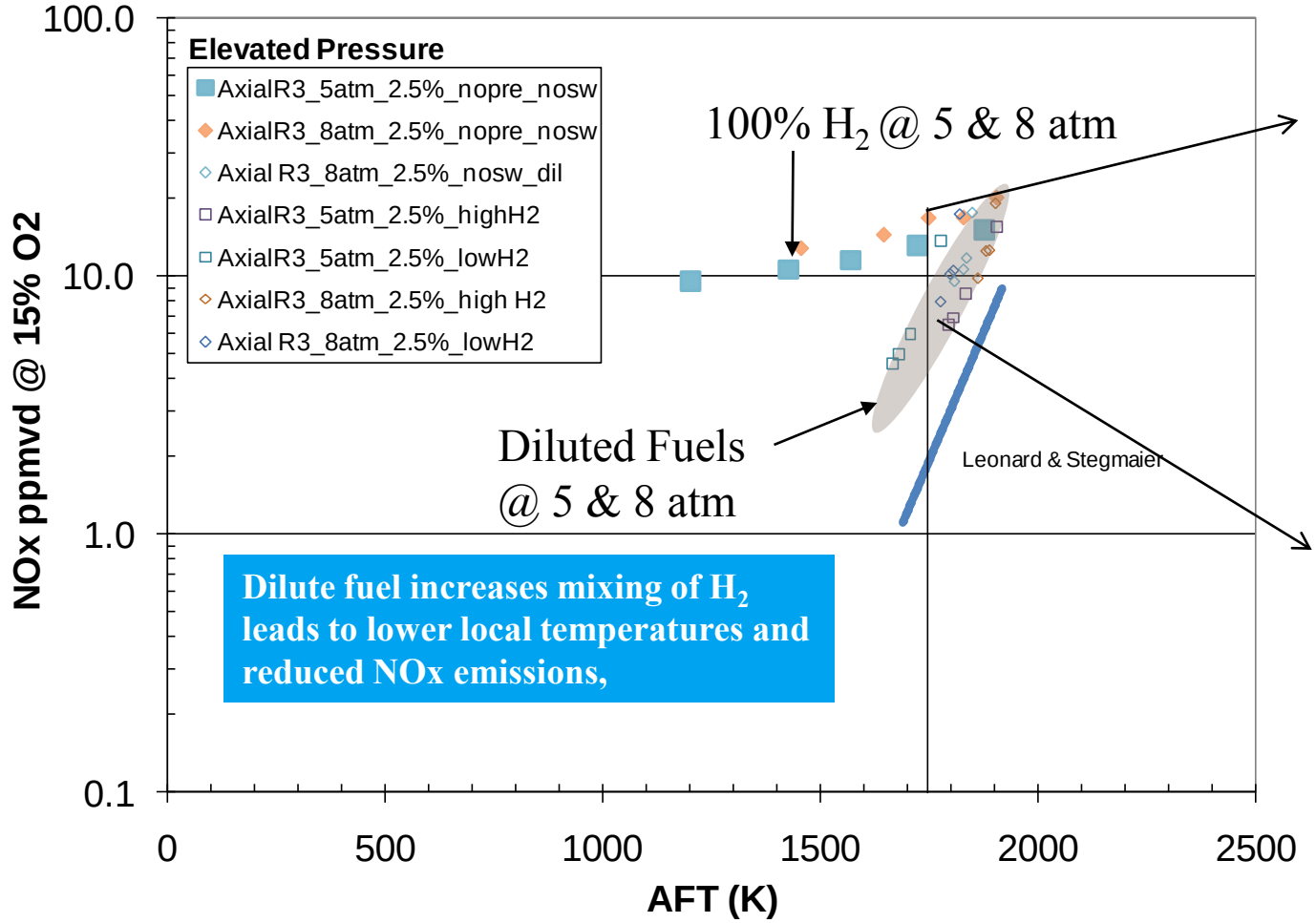
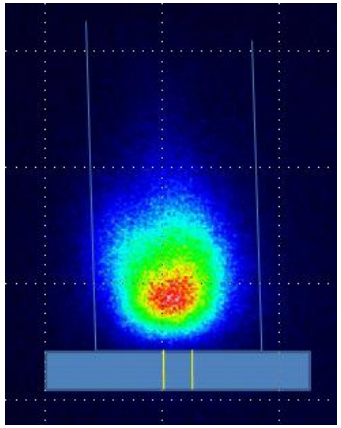
Micro-Mixing Cup – Radial/Axial Airflow Design Emissions using 100% Hydrogen with Dilution

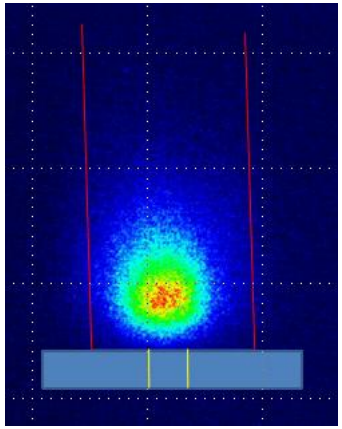
- 100% Hydrogen fuel; up to 30% N_2



Dilute fuel increases mixing of H_2 leads to lower local temperatures and reduced NOx emissions,



8atm – no dilution



8atm – with dilution

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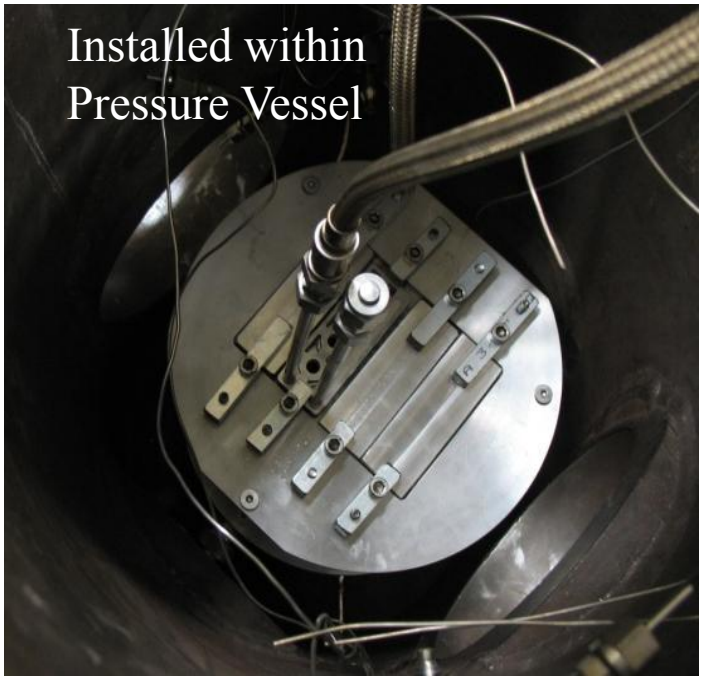
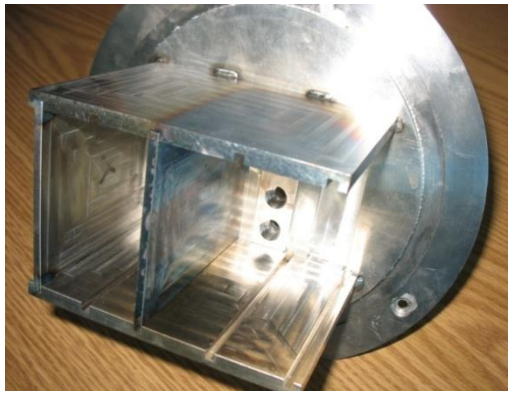
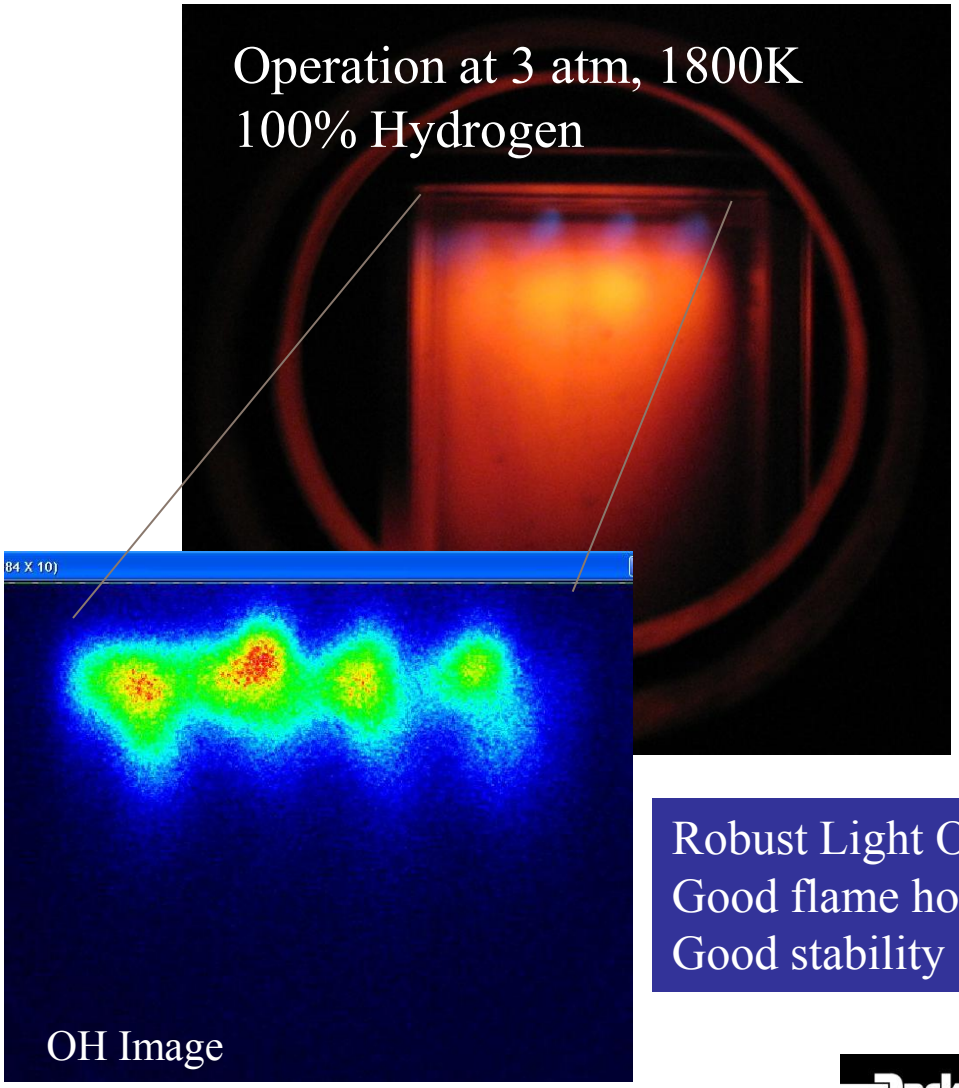
Multi-Cup Injector Module – Radial/Axial Design







Robust Light Off
Good flame holding
Good stability

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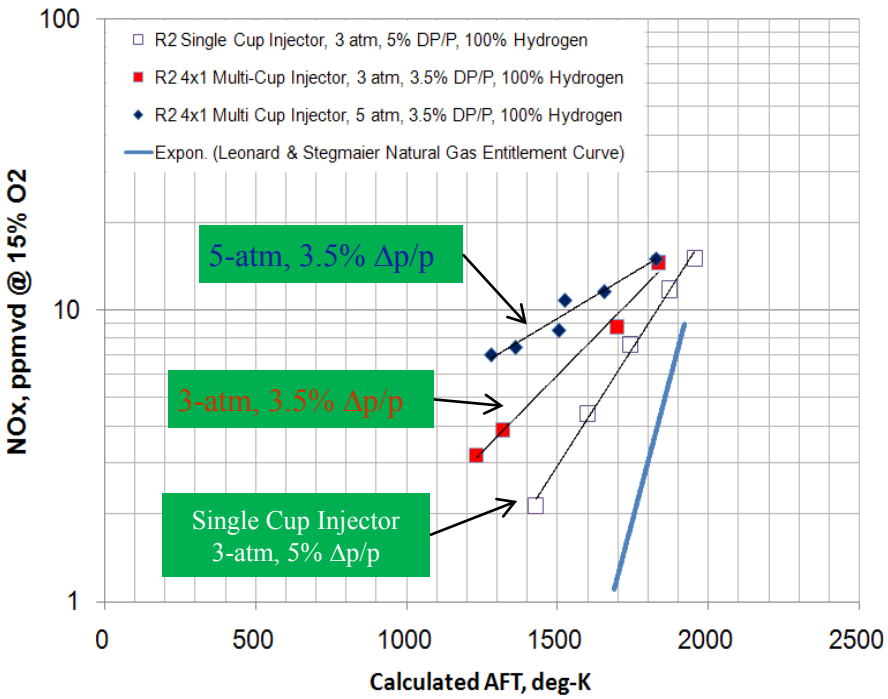
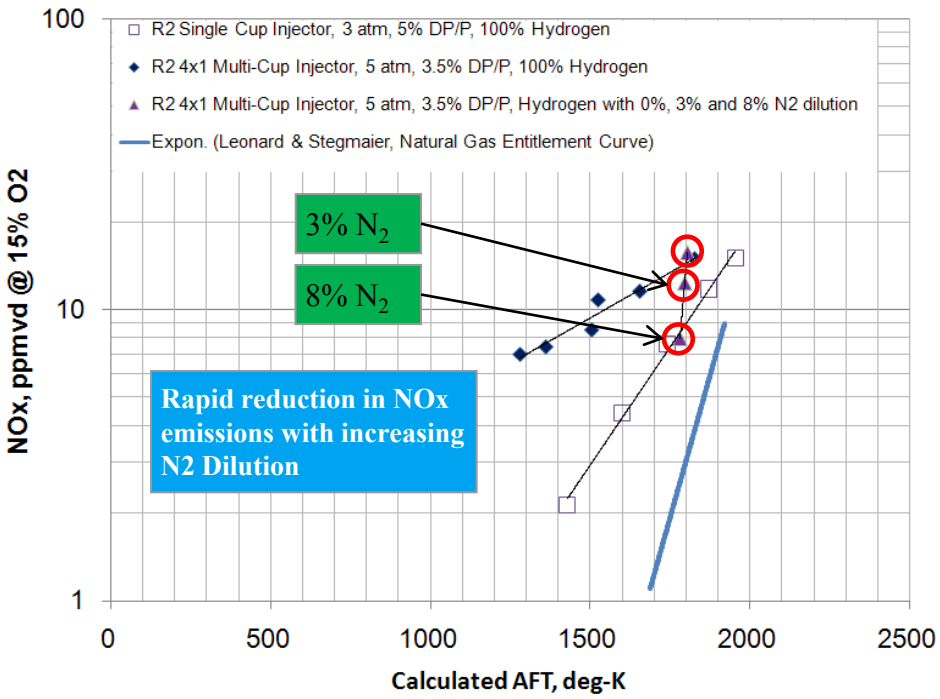
Multi-Cup Injector Module – Radial/Axial Design Emissions Results: 3-atm and 5-atm

- Without Dilution



- With N_2 Dilution



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Micro-Mixing Cup – Radial/Axial Airflow Design Summary

- Operability observations confirm design goals
  - Major accomplishment: No ingress observed with 100% H_2 for a wide range of conditions:
    - 2.5, 3.5, 5.0% DP/P
    - Up to 2000 K temperatures
    - Preheat to 550 K
    - Up to 8 atm
- Emissions levels on target – N2 dilution levels acceptable
  - 20% N2 dilution cuts NOx emissions by 50% to 5-ppm at 1750K AFT.

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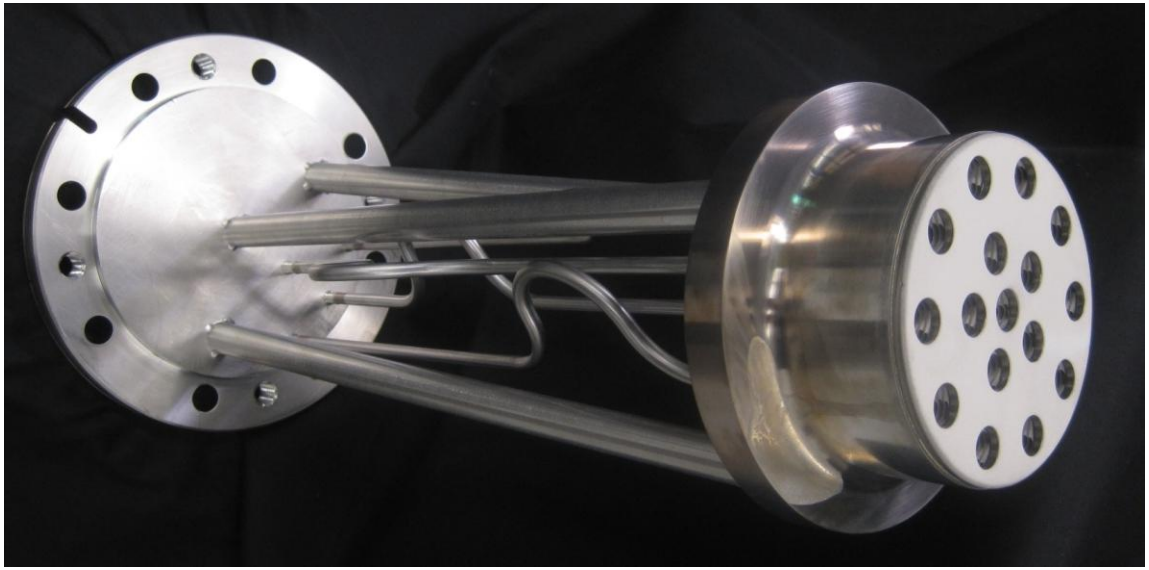
Full-Scale Injector Development: Macrolaminated Construction

Description

- 16 mixing cups
- 1.3-MW_{th} Heat Release (180-psi, ϕ=0.55 Hydrogen)
- 6-cup stage for part-load operation (zone 1)
- Center cup as pilot

Design

- 15 ML plates
- All fuel manifolds integrated into ML structure
- TBC coating on front face



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Full-Scale Injector Testing

- Atmospheric Testing (UCI)
  - Flame imaging & LBO (staged, center 6 cups)
  - Fuel-air mixing studies
  - Emissions tests (staged, center 6 cups)

- High-Pressure Testing
  - Conditions representative of full-scale engines
    - 100psi – 180psi, 3.2% to 4.0% pressure drop, 650°F to 900°F inlet air
    - 100% Hydrogen
    - 100% Natural Gas
    - H_2 and Natural Gas mixtures with diluents
  - Emissions and operability tests

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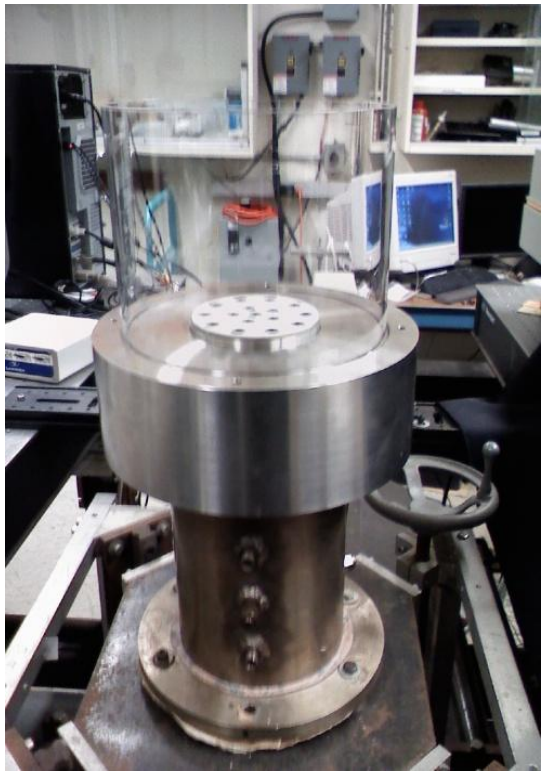
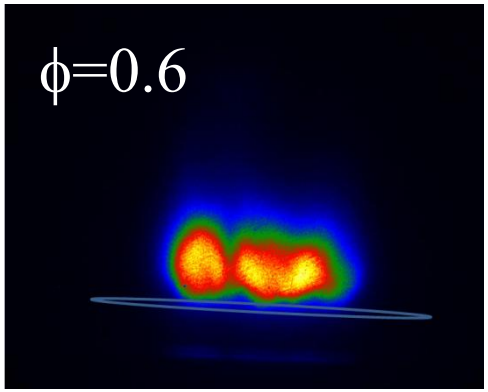
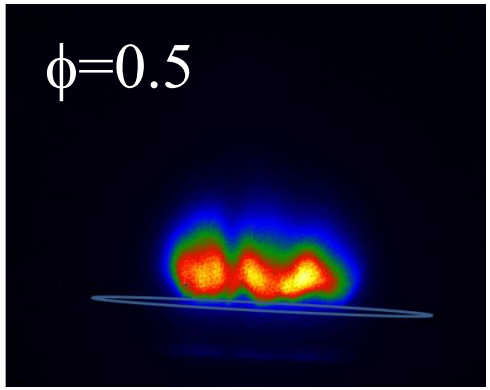
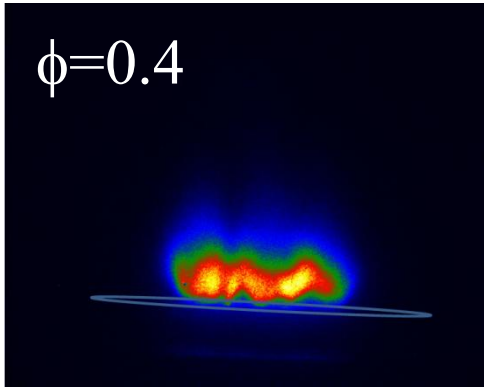
Full-Scale Injector – Atmospheric Testing Flame Imaging, LBO (center six cups)

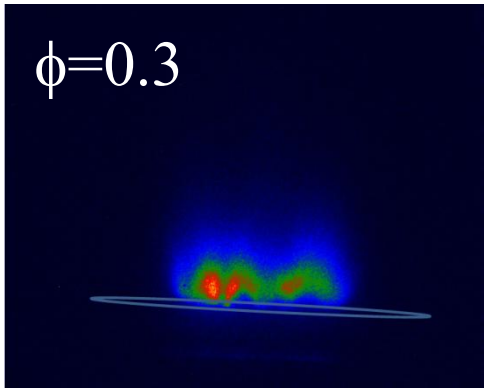
- 100% Hydrogen Fuel











- Lifted flames at all conditions, no ingress
- LBO at local ϕ of 0.27 (global ϕ of 0.1)

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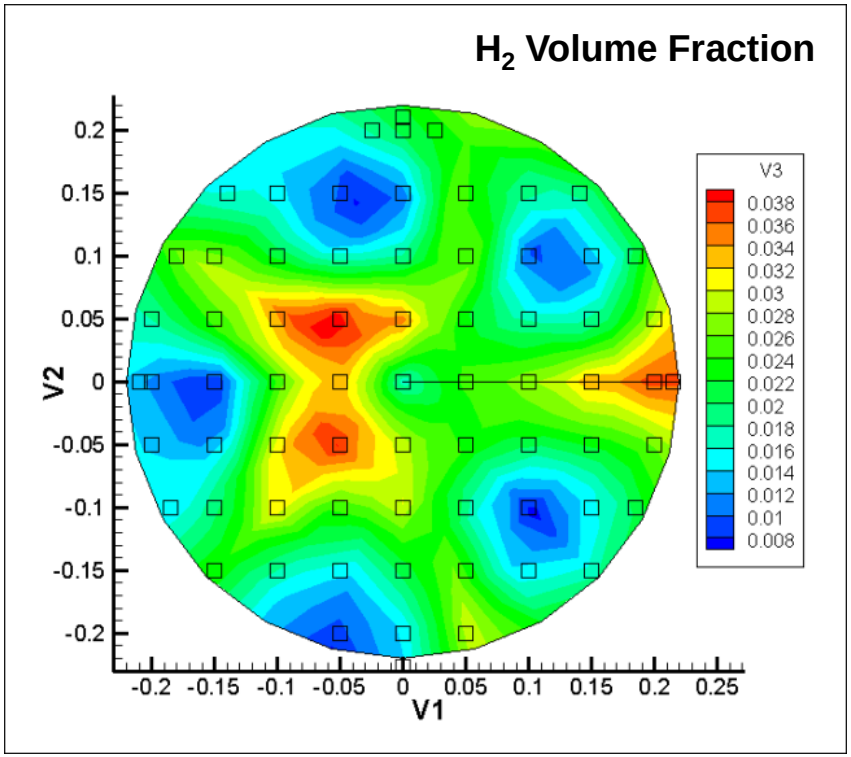
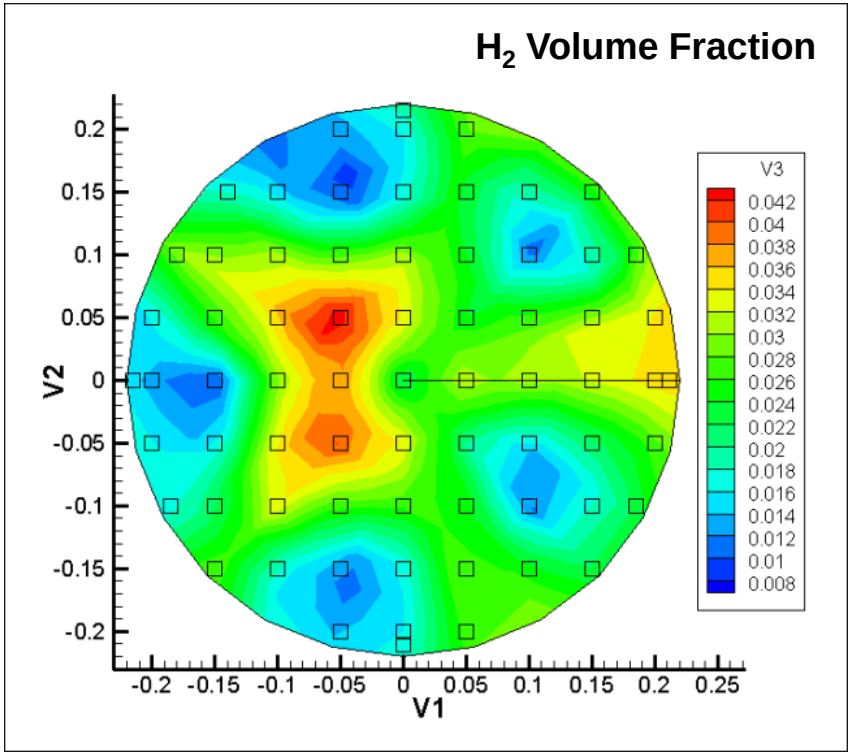
Full-Scale Injector – Atmospheric Testing Hydrogen-Air Mixing

Pilot cup: Effect of pressure drop (Equivalence ratio of 0.5)



3.5% ΔP/P



4.5% ΔP/P

Fuel concentration measured using extractive probe at the mixing cup exit

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Full-Scale Injector – High-Pressure Testing

- Operating pressure
  - 100psi, 120psi180 psi, (6.9 bar, 8.4 bar, 12.4 bar)
- Pressure drop
  - 3.2%, 3.5%, 4.0%, 4.5%
- Inlet air temperature
  - 615K (650°F), 700K (800°F), 755K (900°F)
- Pilot setting
  - Lean, neutral, enriched
- Hydrogen content (hydrogen / natural gas mixture)
  - 0%, 50%, 86%, 93%, 100%
- Diluent
  - Nitrogen, Carbon dioxide
  - 0% - 40% dilution

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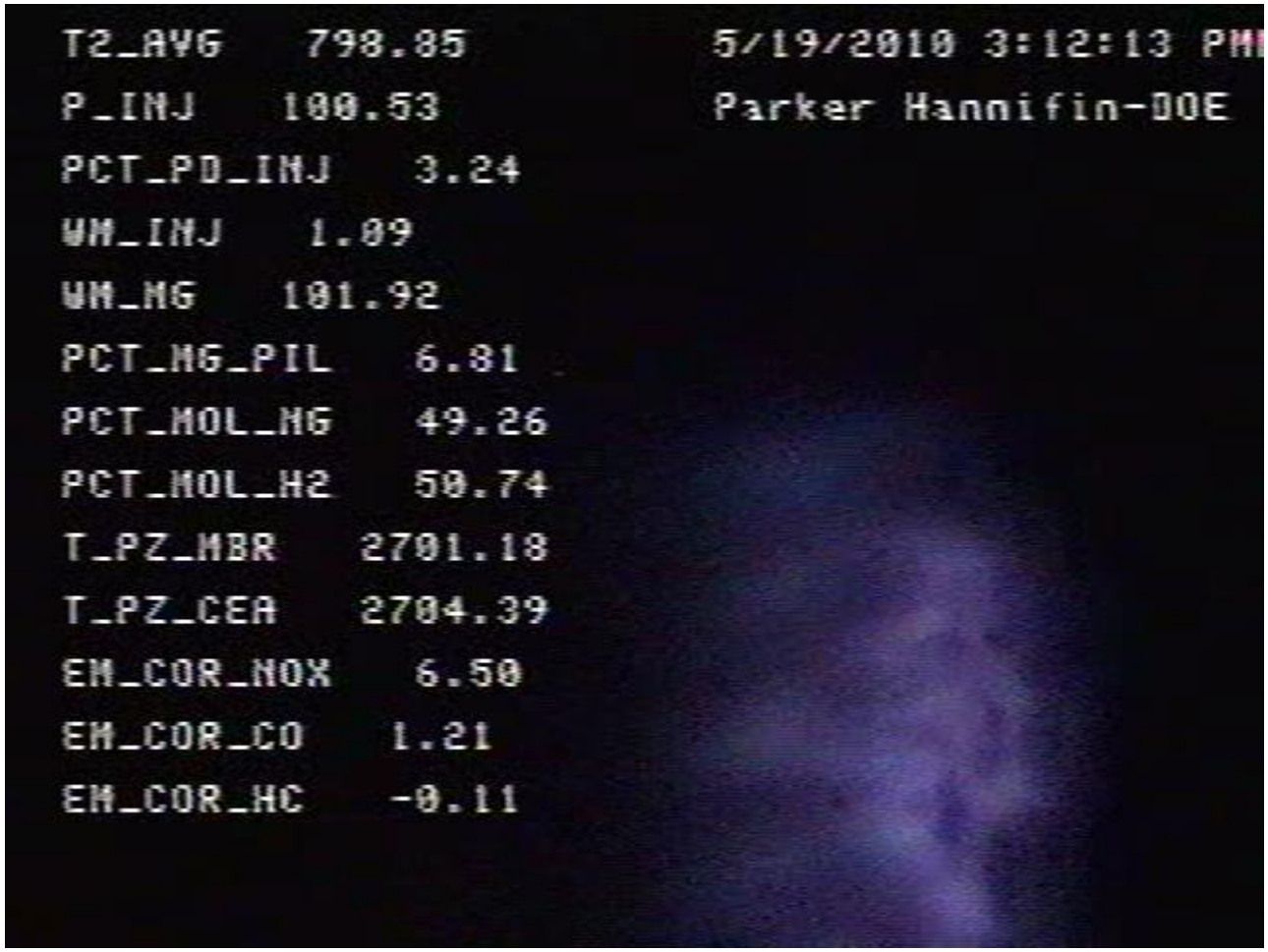
Full-Scale Injector – High-Pressure Testing Visual Flame for H2/NG Mixture



Conditions:

- 50% / 50% H2/NG
- No dilution
- 2700°F AFT (1755K)
- Neutral pilot
- 6.5 ppm NOx

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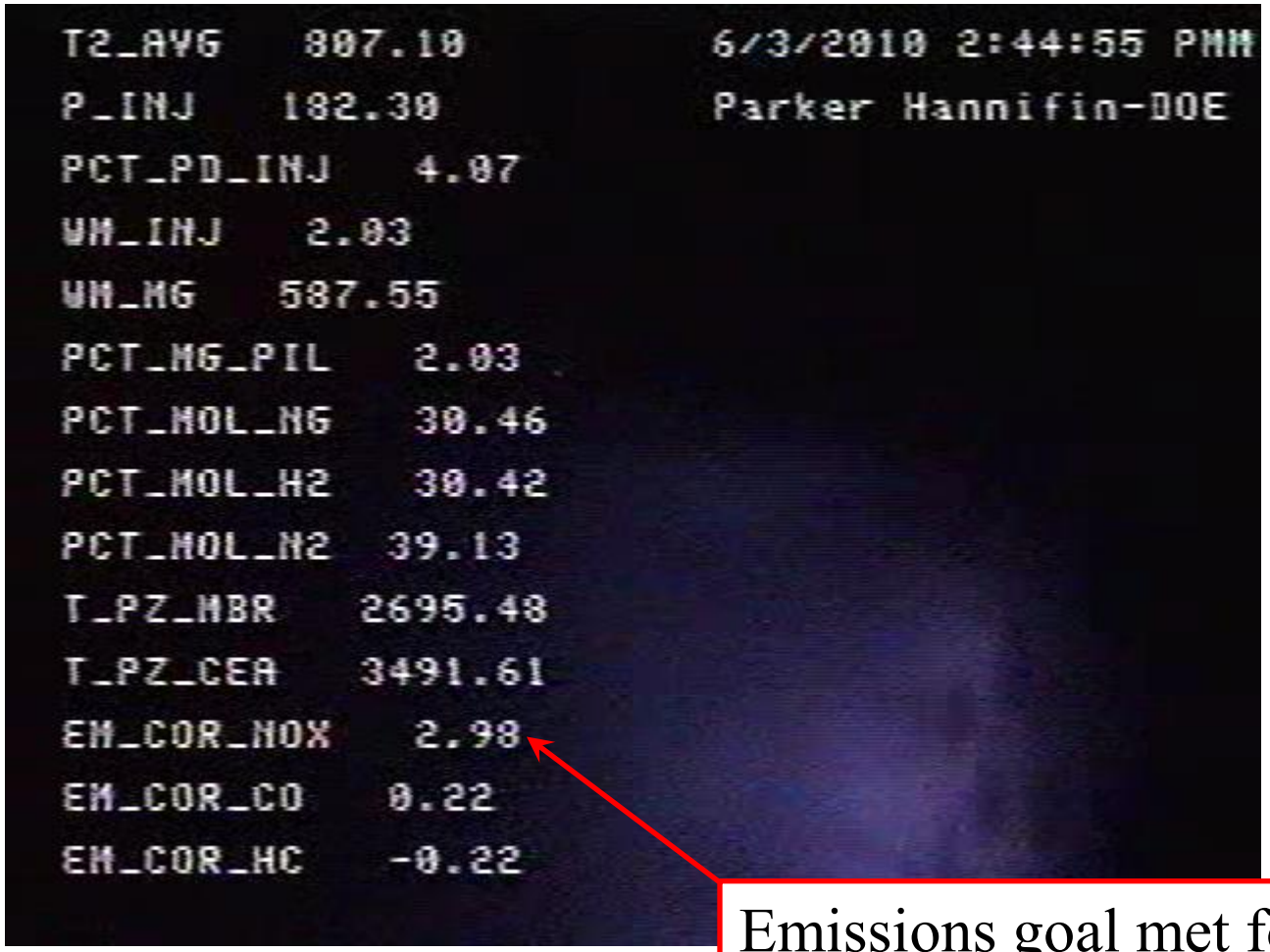
Full-Scale Injector – High-Pressure Testing
Visual Flame H2/NG Mixture with N2 dilution



Conditions:

- 50% / 50% H2/NG
- 40% N2 dilution
- 2695°F AFT (1753K)
- Slightly lean pilot
- 3 ppm NOx

Emissions goal met for the 50/50 H2/NG fuel mixture

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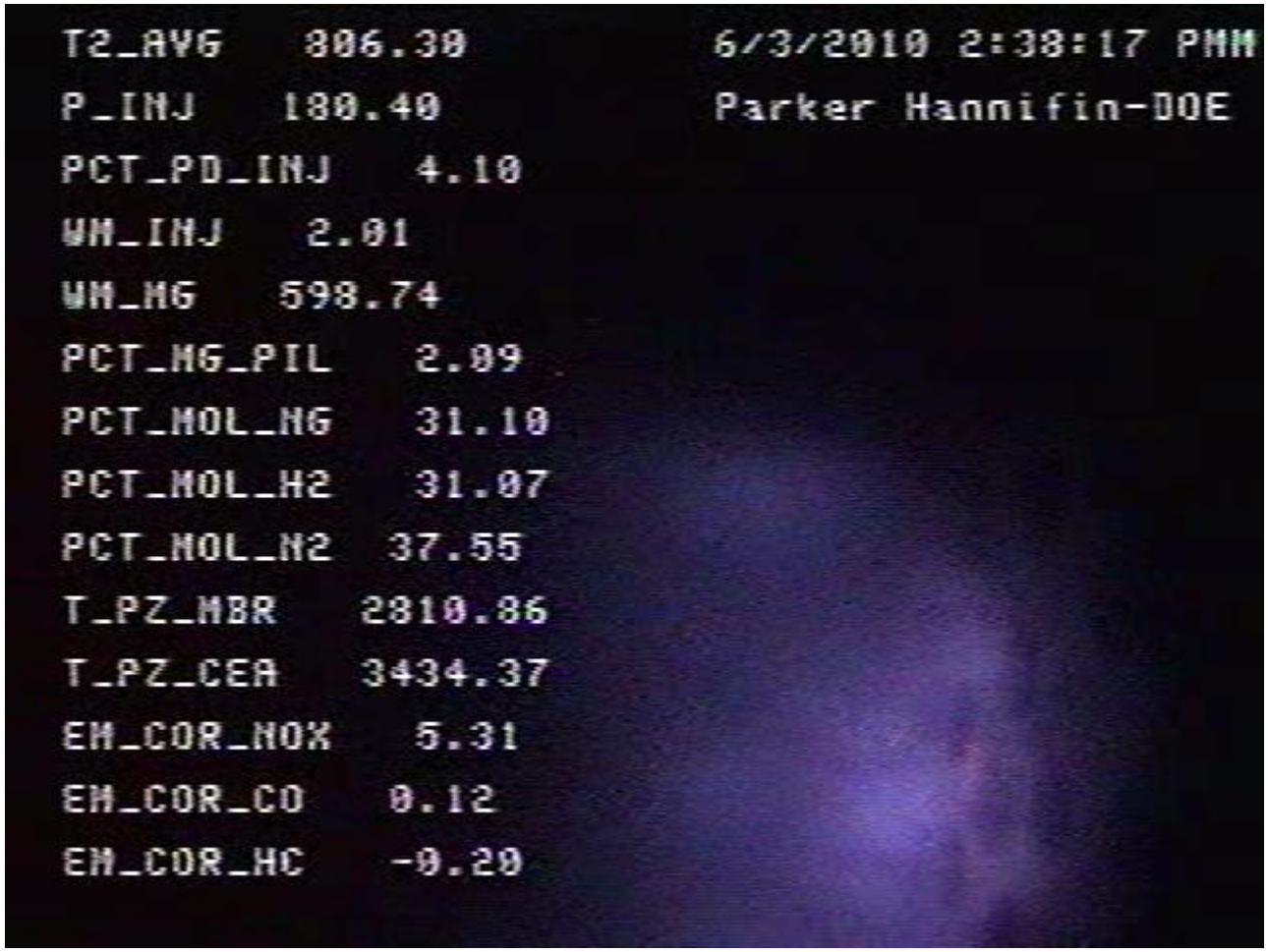
Full-Scale Injector – High-Pressure Testing
Visual Flame – H2/NG Fuel, N2 dilution, High AFT



Conditions:

- 50% / 50% H2/NG
- 38% N2 dilution
- 2810°F AFT (1861K)
- Slightly lean pilot
- 5.3 ppm NOx

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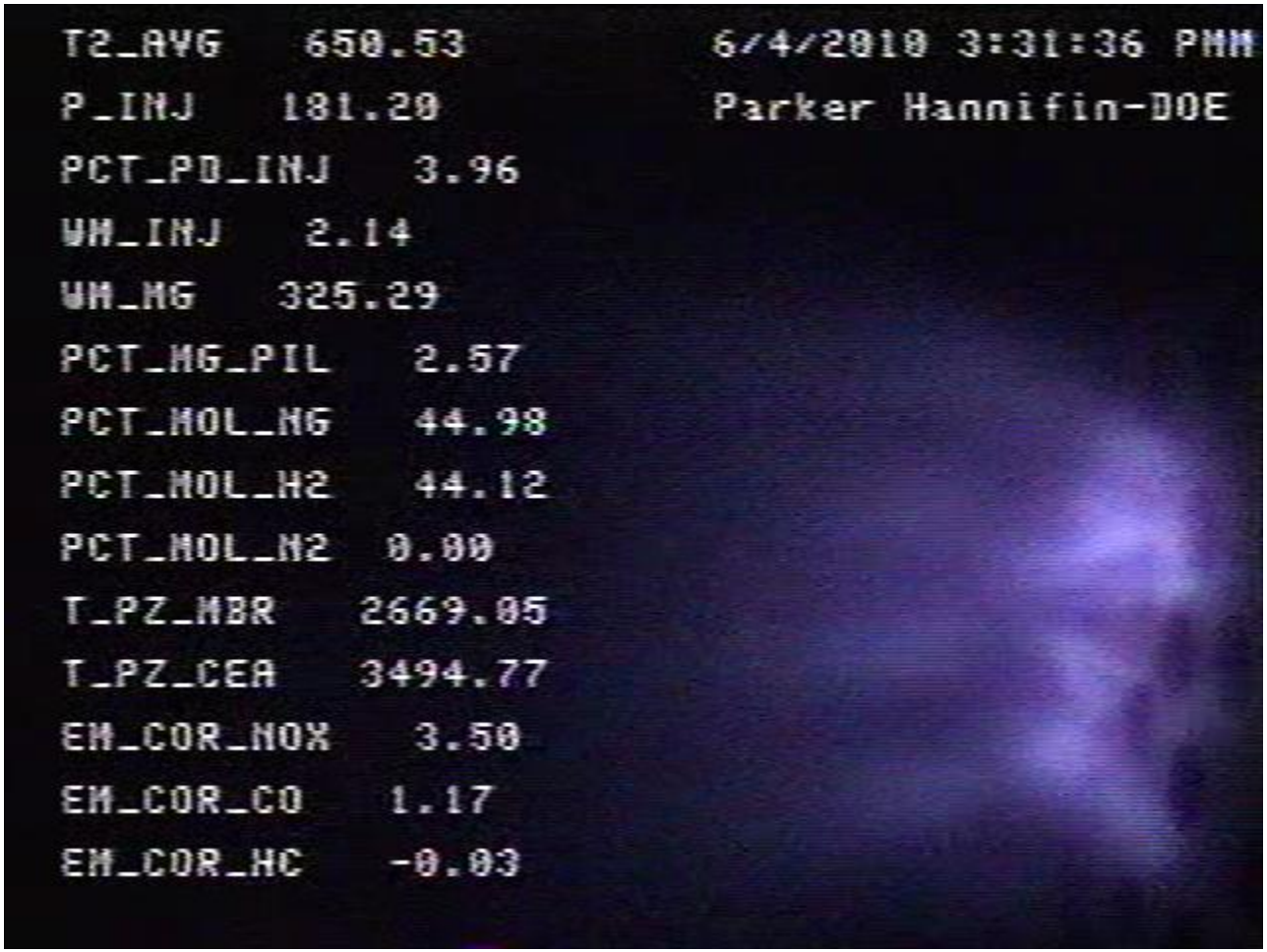
Full-Scale Injector – High-Pressure Testing Visual Flame H2/NG Fuel with CO2 dilution



Conditions:

- 50% / 50% H2/NG
- 10% CO2 dilution
- 2669°F AFT (1738K)
- Neutral pilot
- 3.5 ppm NOx

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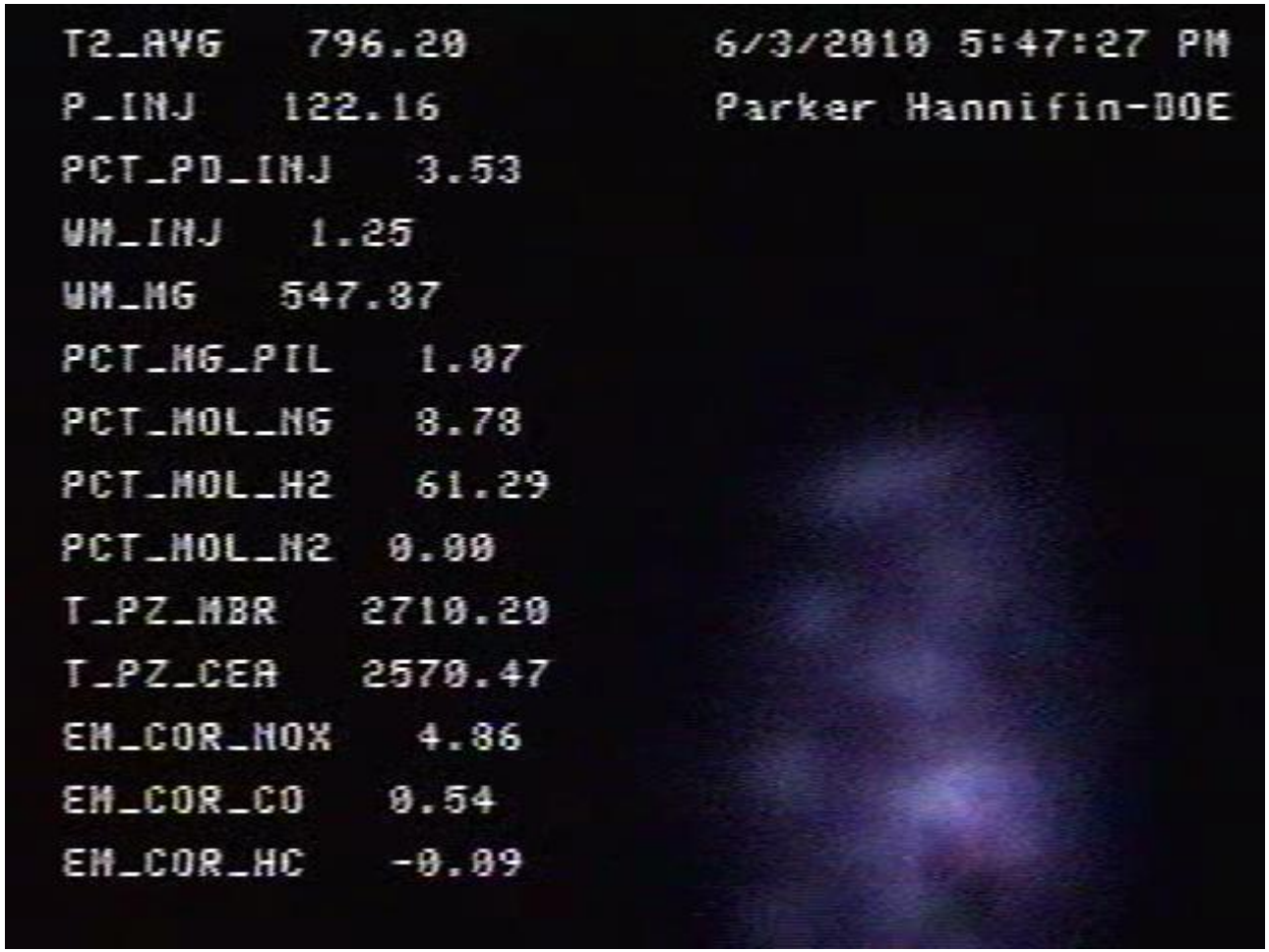
Full-Scale Injector – High-Pressure Testing
Visual Flame 86% H2, 14%NG Fuel, CO2 dilution



Conditions:

- 86% / 14% H2/NG
- 30% CO2 dilution
- 2710°F AFT (1761K)
- Leaned pilot
- <5 ppm NOx

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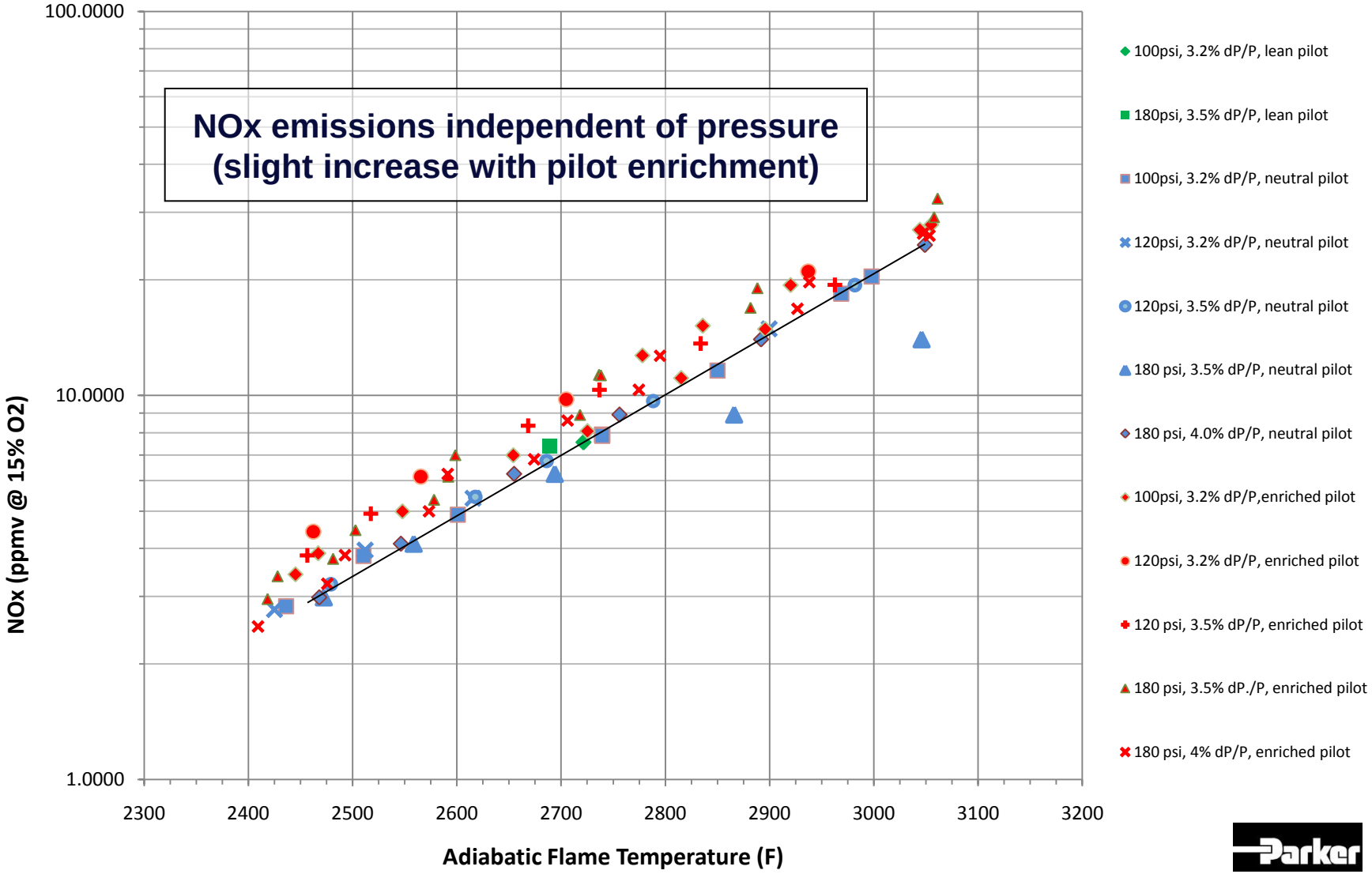
Full-Scale Injector – High-Pressure Testing
NOx Emissions: 50/50 H2/NG Fuel Without Diluents



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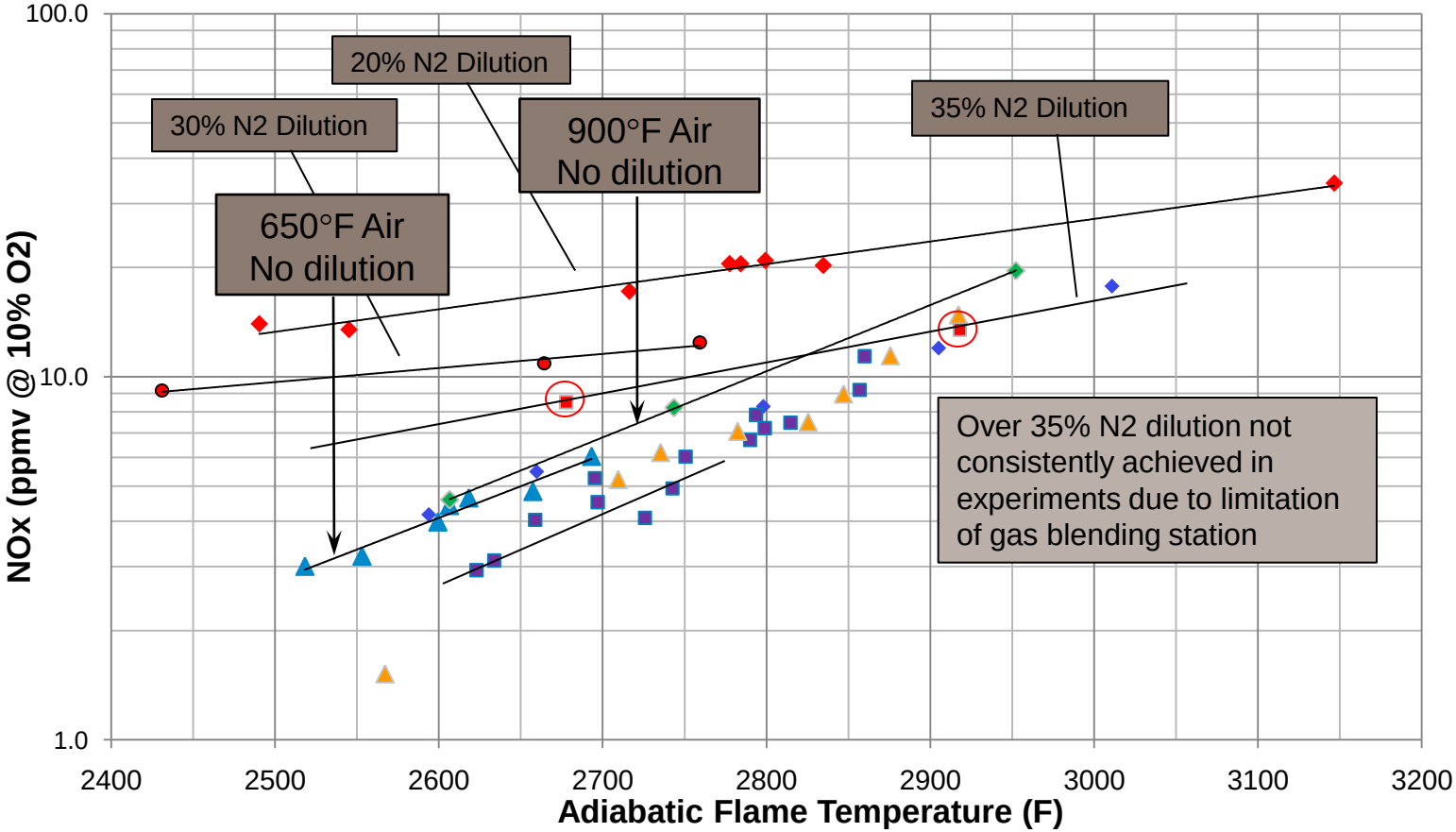
Full-Scale Injector – High-Pressure Testing
NOx Emissions: H2/NG mixtures w/wo N2 Dilution



- 50% H2, 50% NG, No Dilution, 650F Air
- 50% H2, 50% NG, No dilution, 800F Air
- 50% H2, 50% NG, No Dilution, 900F Air
- 50% H2, 50% NG, N2 Dilution, 800F Air
- 50% H2, 50% NG, N2 Dilution, 900F Air
- 86% H2, 14% NG, 20% N2 Dilution, 800F Air
- 86% H2, 14% NG, 30% N2 Dilution, 800F Air
- 86% H2, 14% NG, 35% N2 Dilution, 800F Air

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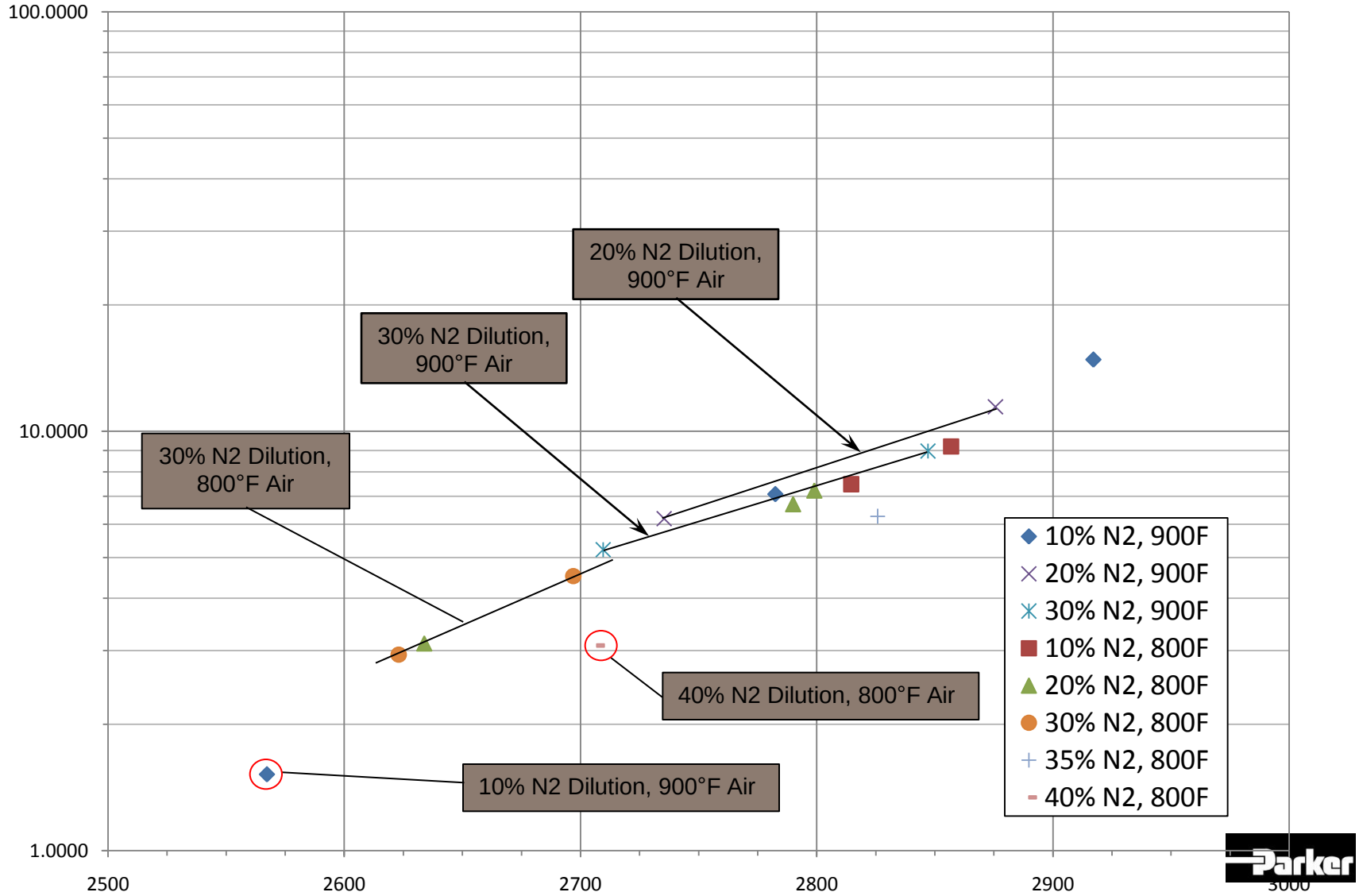
Full-Scale Injector – High-Pressure Testing
NOx Emissions: 50/50 H2/NG mixture, N2 Dilution



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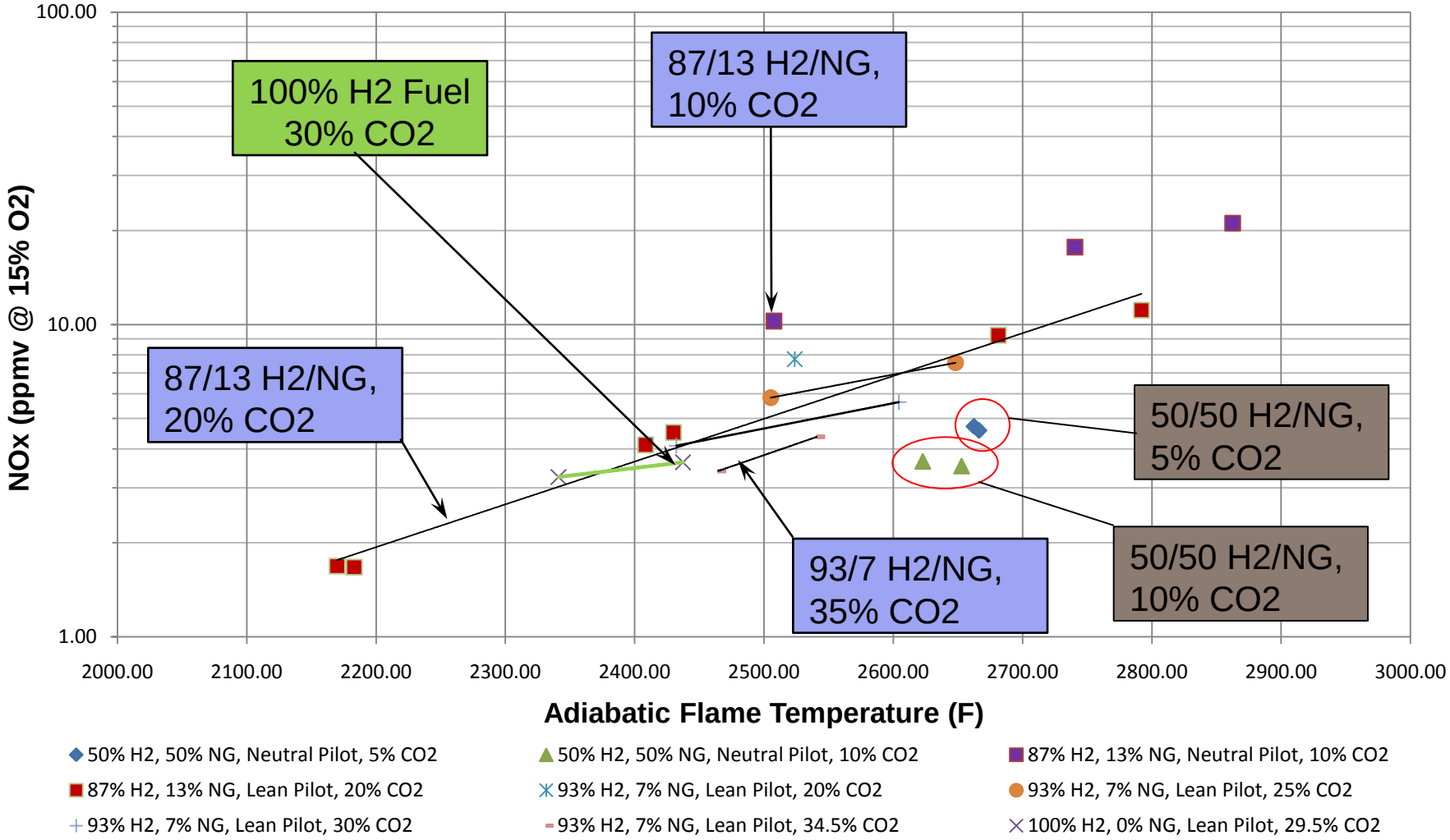
Full-Scale Injector – High-Pressure Testing
NOx Emissions: H2/NG Mixtures, CO2 Dilution



Malfunction of a valve in high-pressure rig near the end of the test campaign preempted tests on 100% hydrogen at higher adiabatic flame temperatures than recorded here.

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High-Pressure Testing – Summary of Emissions Results

- Ultra-low NOx emissions demonstrated
  - At or near 3-ppm goal at target 1750K flame temperature for different mixtures and conditions
- For 50% hydrogen and 50% natural gas fuel mixture:
  - 1.5-ppm NOx at AFT over 1680K (2564°F) with 10% nitrogen dilution
  - 3-ppm NOx at AFT of 1750K (2690°F) with 40% nitrogen dilution.
  - 3.5-ppm NOx at AFT of 1730K (2650°F) with 10% carbon dioxide dilution
  - 6-ppm at AFT of 1750K (2690°F) with no dilution
- For 100% hydrogen fuel:
  - 3.6-ppm NOx AFT over 1600K (2420°F) with 30% CO2 dilution

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High-Pressure Testing – Summary

- Operation on hydrogen-natural gas mixtures with 50%-100% hydrogen content demonstrated
  - High turndown demonstrated for high-hydrogen fuel mixtures
    - 2400°F on 50% hydrogen
    - 2200°F on 86% hydrogen (with dilution)
  - Operation without flashback over a wide range of operating conditions on fuel mixtures containing up to 100% hydrogen

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Conclusions

- Basic building block for the micro-mixing multi-cup injector technology has been fully validated
- Viability of the technology for high-hydrogen fuels has been demonstrated
- Technology is adaptable to gas turbine engines of any size

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Thank You!

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