Development and Application of Multipoint Array Injection Concepts for Operation of Gas Turbines on Hydrogen Containing Fuels

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2023 UTSR Workshop
30 Oct – 1 Nov 2023

Matt Adams, Technical Monitor

UCI Combustion Laboratory
UCIrvine | University of California

Solar Turbines
A Caterpillar Company

Collins Aerospace

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30 October 2023
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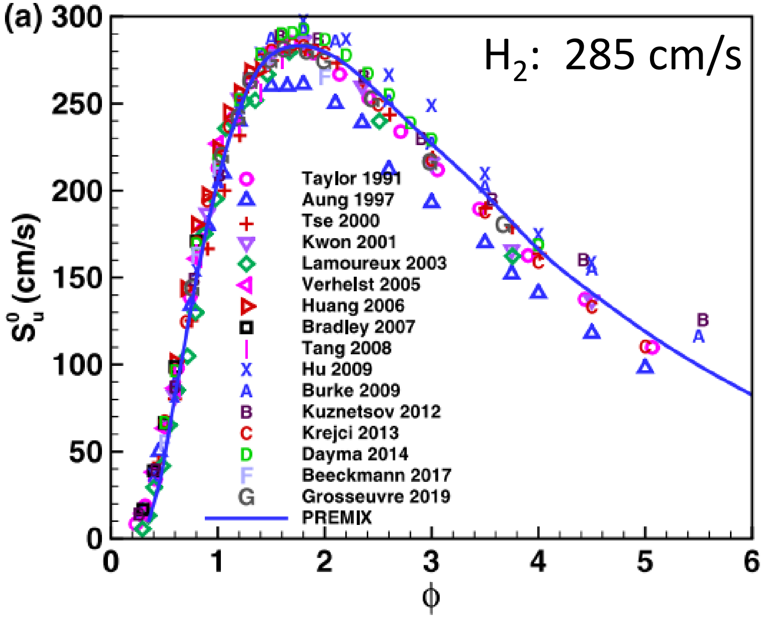
Outline

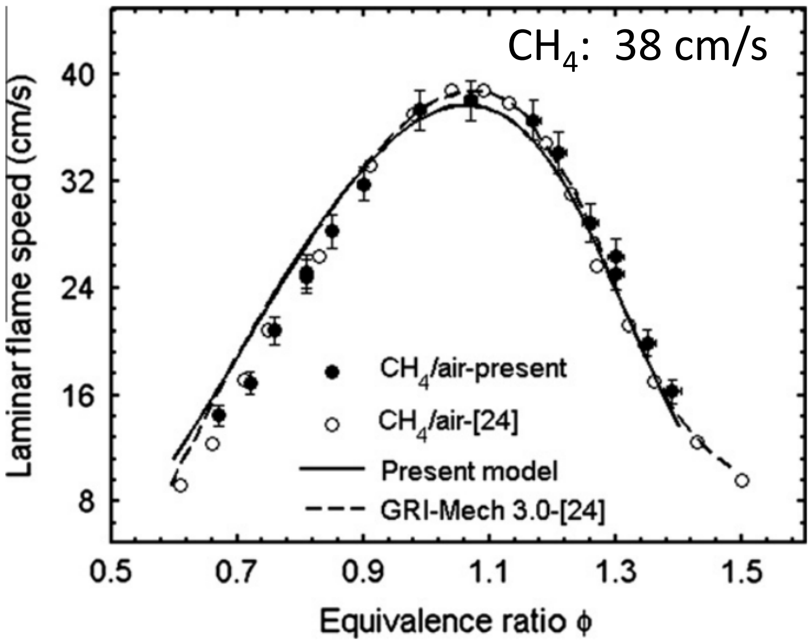
- Background
- Project objective(s)
- Technical approach
  - Team
  - Tasks
  - Schedule
- Results/Conclusions
- Next Steps

Perspective

- **Jet-A vs Hydrogen vs Methane relative maximum laminar flame speeds**
  - **H_2: 285 cm/s; CH_4: 38 cm/s; Jet-A: 92 cm/s**
  - **Flashback risk for Jet-A > than for natural gas**
    - ✓ **Aero applications less tolerance for risk (avoid lean premixed strategies)**

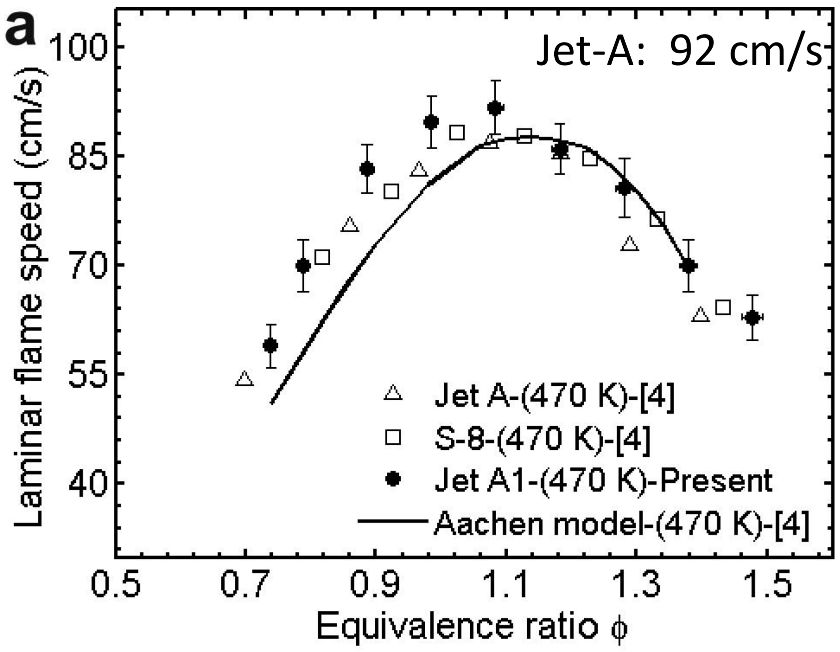


Han, et al., (2020). Laminar flame speeds of hydrogen and syngas measured from spherical flames, *App. Energy and Combustion Science*, 1-4, pg 100008.



. 5. Laminar flame speed for methane/air mixture at 298 K and 1 atm. (●) esent, (○) Vagelopoulos et al. [24], (—) present model, (- - -) GRI-Mech 3.0 [24].

Chong and Hochgreb (2011). Measurements of laminar flame speeds of acetone/methane/air mixtures, *Combustion and Fuel*, Vol 158, 490-500



Chong and Hochgreb (2011). Measurements of laminar flame speeds of liquid fuels: Jet A-1, diesel, palm methyl esters, and blends using particle image velocimetry, *Proc of Combustion Institute*, Vol 33, 979-986.

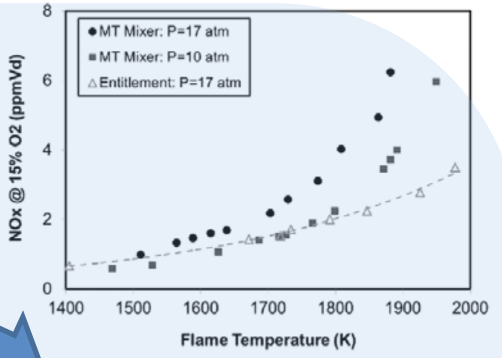
Prior/Current Work

Paths forward for ground based 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

GE: <9ppm

York, et al. (2013).



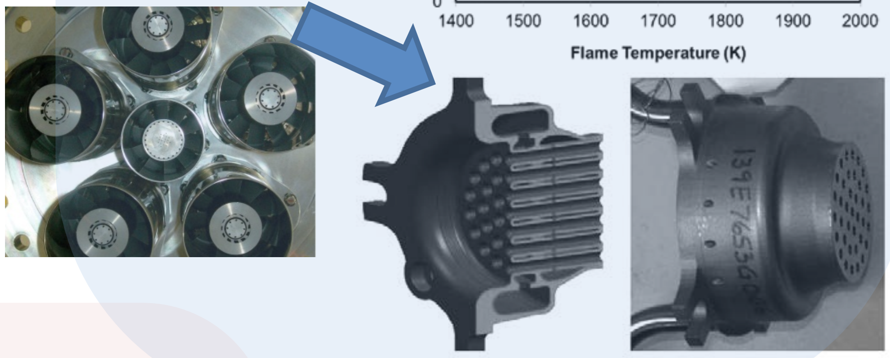
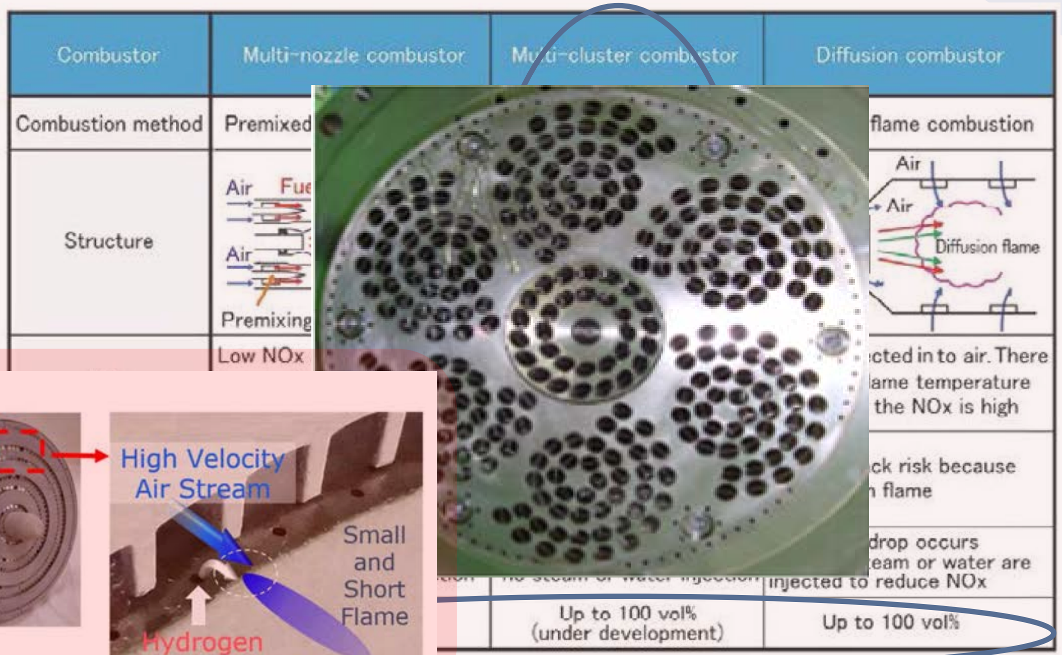
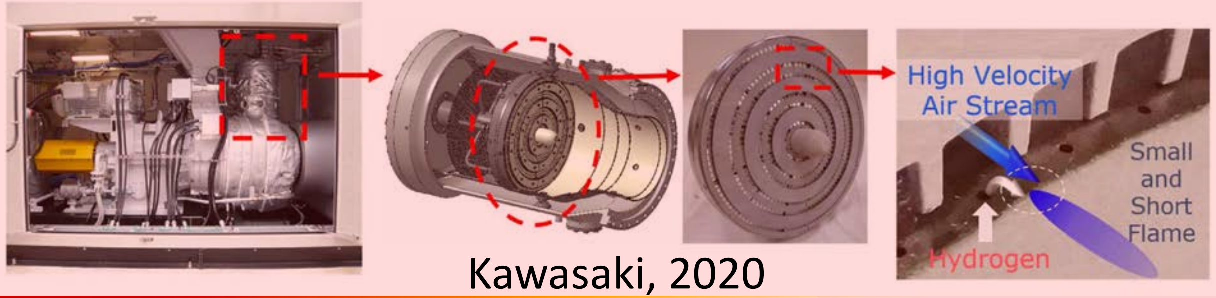


Fig. 2 Model cross section and photograph of small multitube mixer for high-hydrogen fuel

Mitsubishi

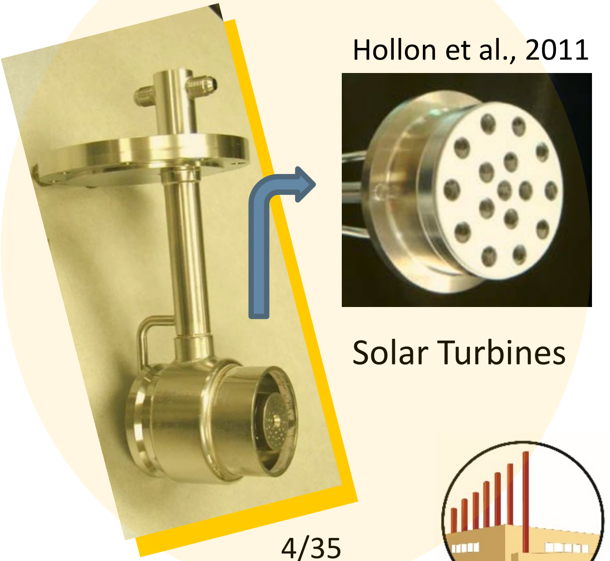


MHPS (2019). H_2 Power Generation Handbook



Kawasaki, 2020

Hollon et al., 2011

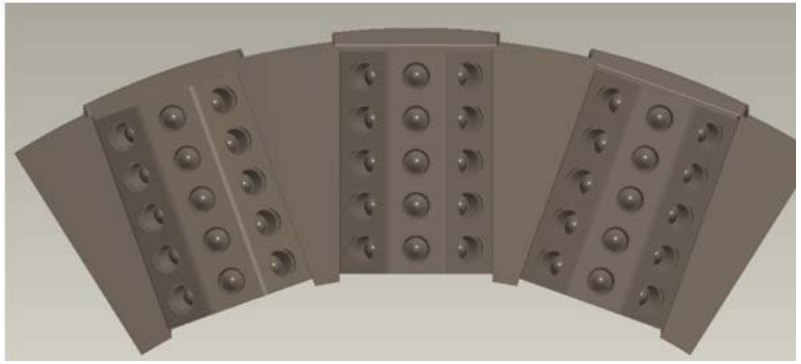


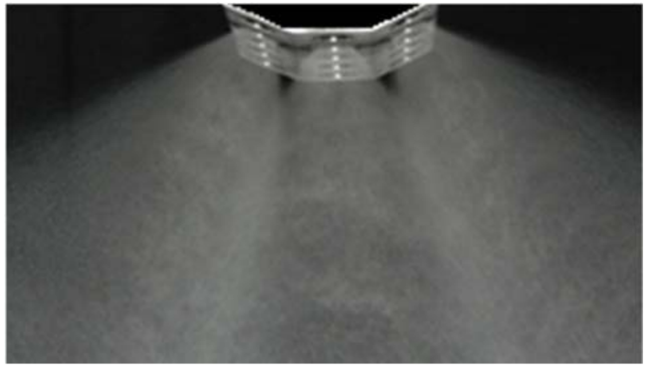
Solar Turbines

Prior Work

- **Aeroengine Context***

Parker





Collins

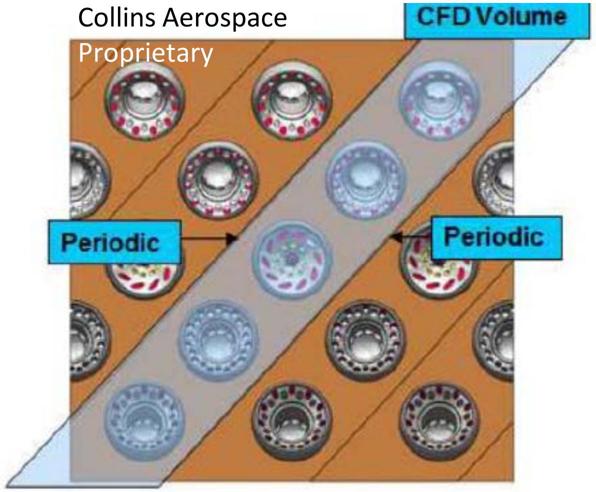
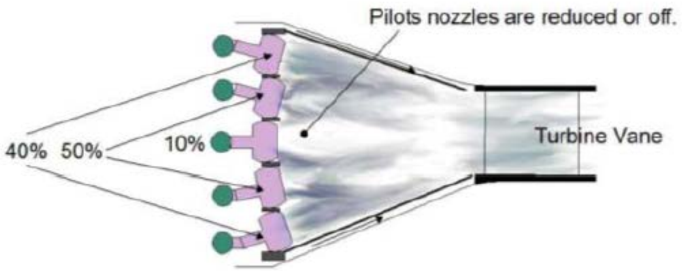
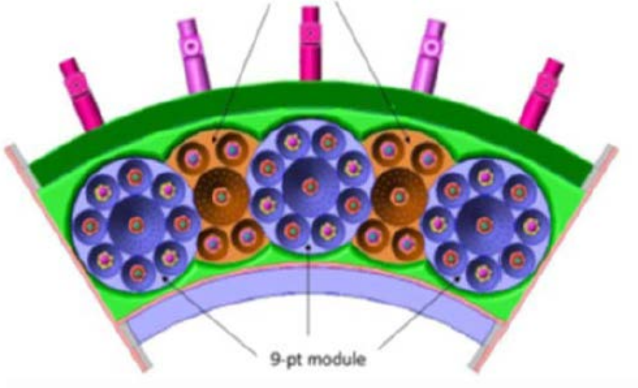


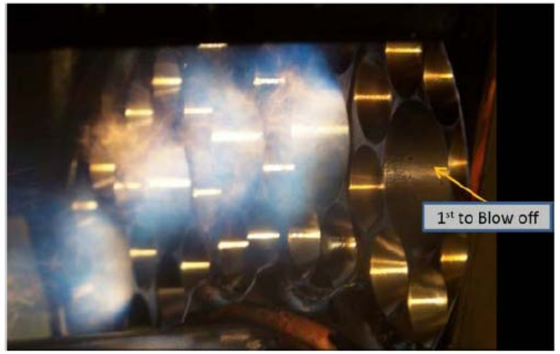
Figure 12 CFD assessment strategy. From ref. [2]



At high power, adjacent nozzles become dominant.
Combustor runs lean. Core effects are diminished

Woodward

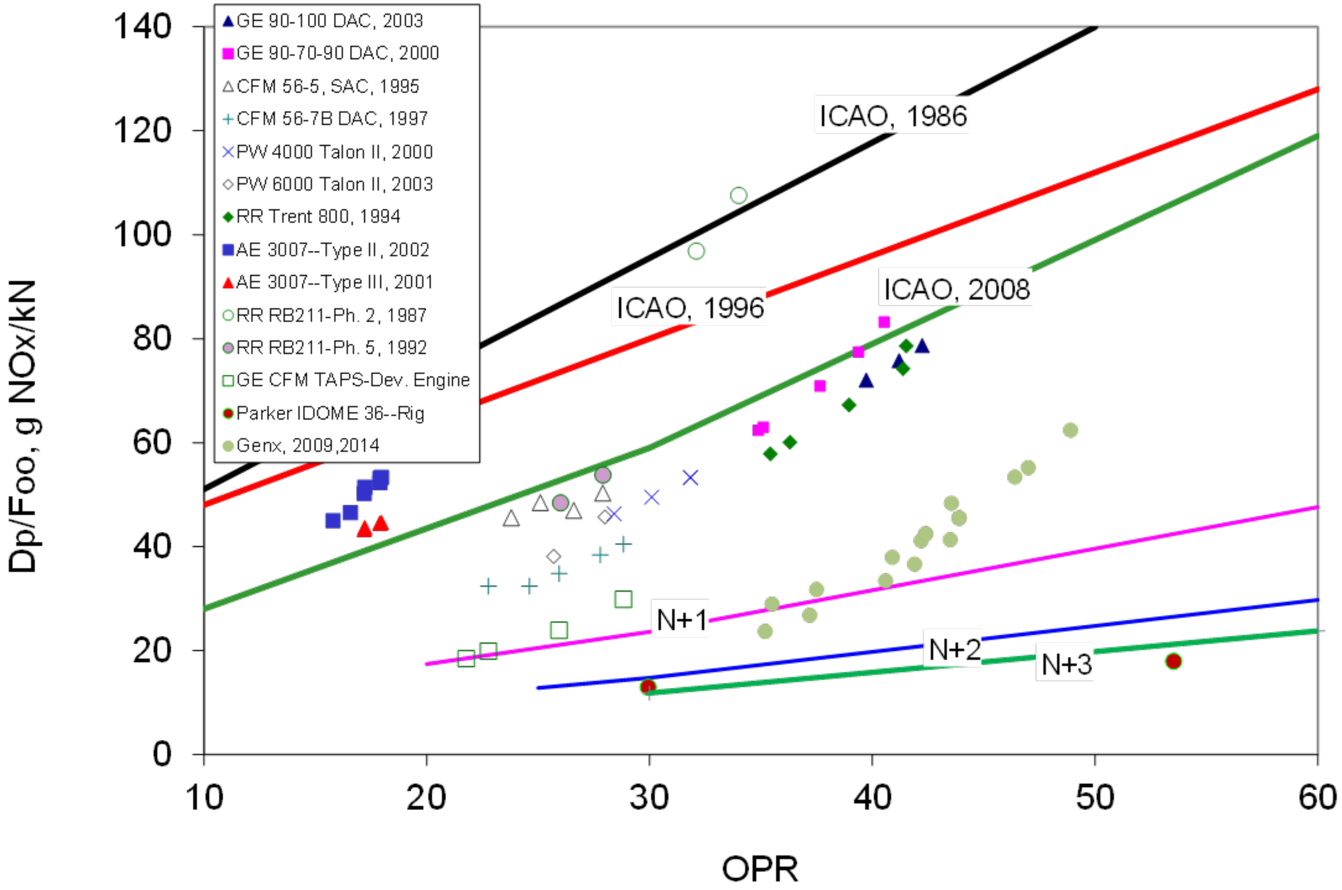


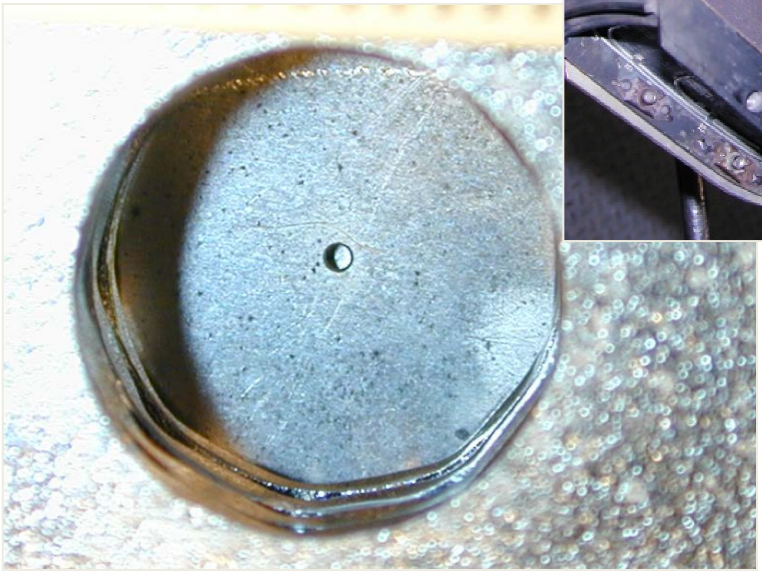


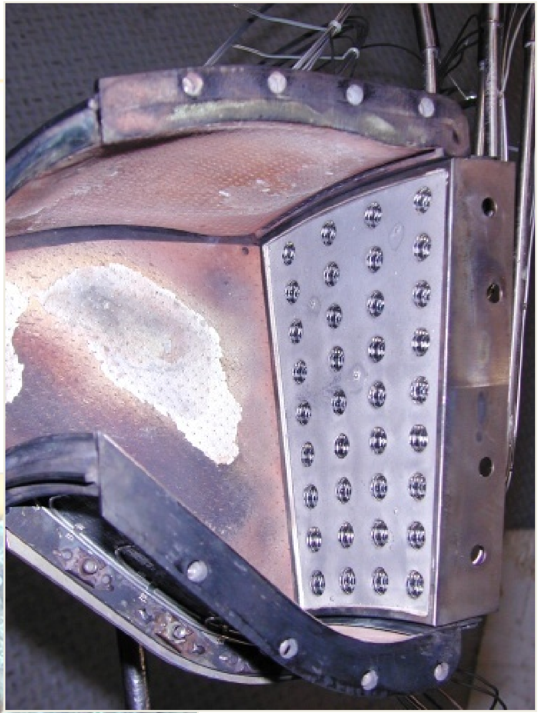
* C.M. Lee, C. Chang, S. Kramer, and J. Herbon (2013). NASA project develops next generation low-emissions combustor technologies, Paper AIAA-2013-0540

Prior Work

- **Aeroengine Context***





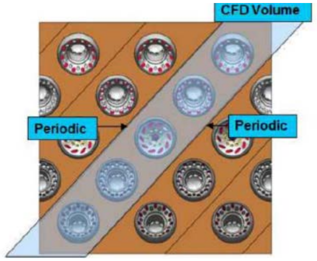


* McDonell, V.G. (2021). Emissions Reduction Technologies for Large Engine—UCICL Gas Turbine Combustion Short Course

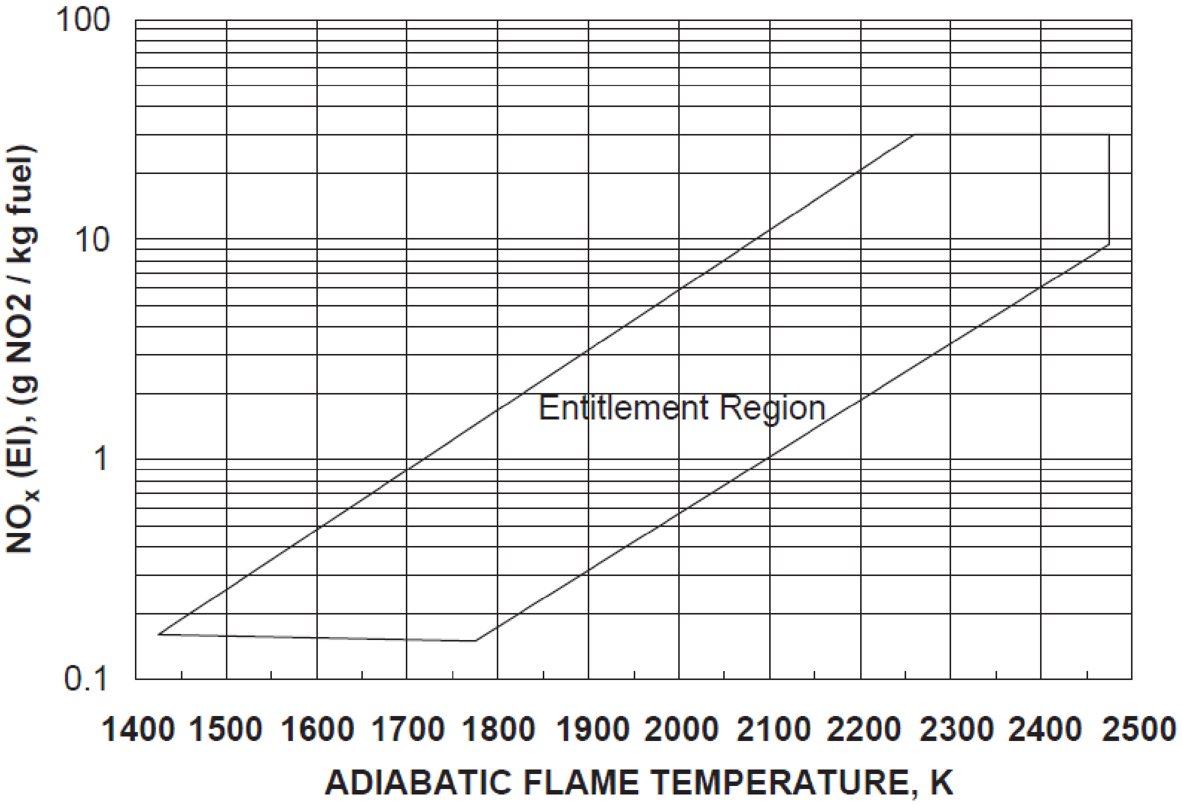
R. Tacina, A. Mansour, L. Partelow, and C. Wey (2004). Experimental Sector and Flame-Tube Evaluations of a Multipoint Integrated Module Concept for Low Emission Combustors, Paper GT2004-53263, Turbo Expo 2004, Vienna

Prior Work

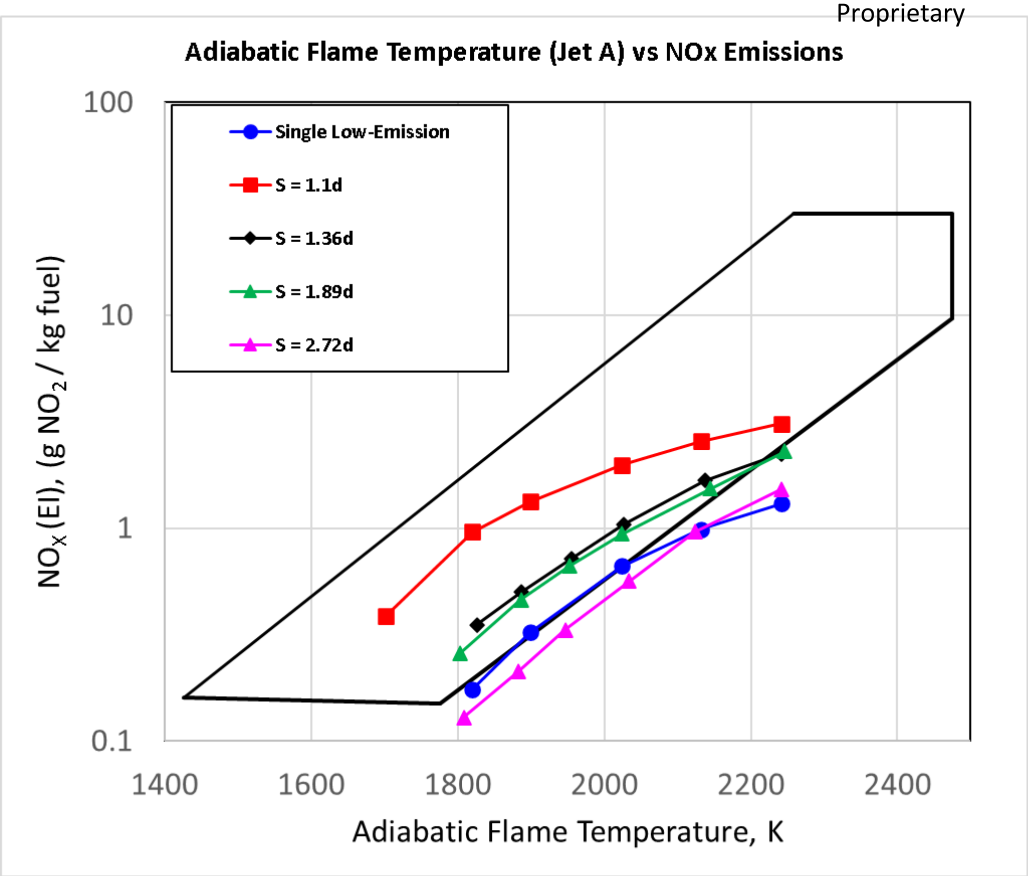
- **Aeroengine Context: NOx "Entitlement"**



Collins Aerospace Proprietary



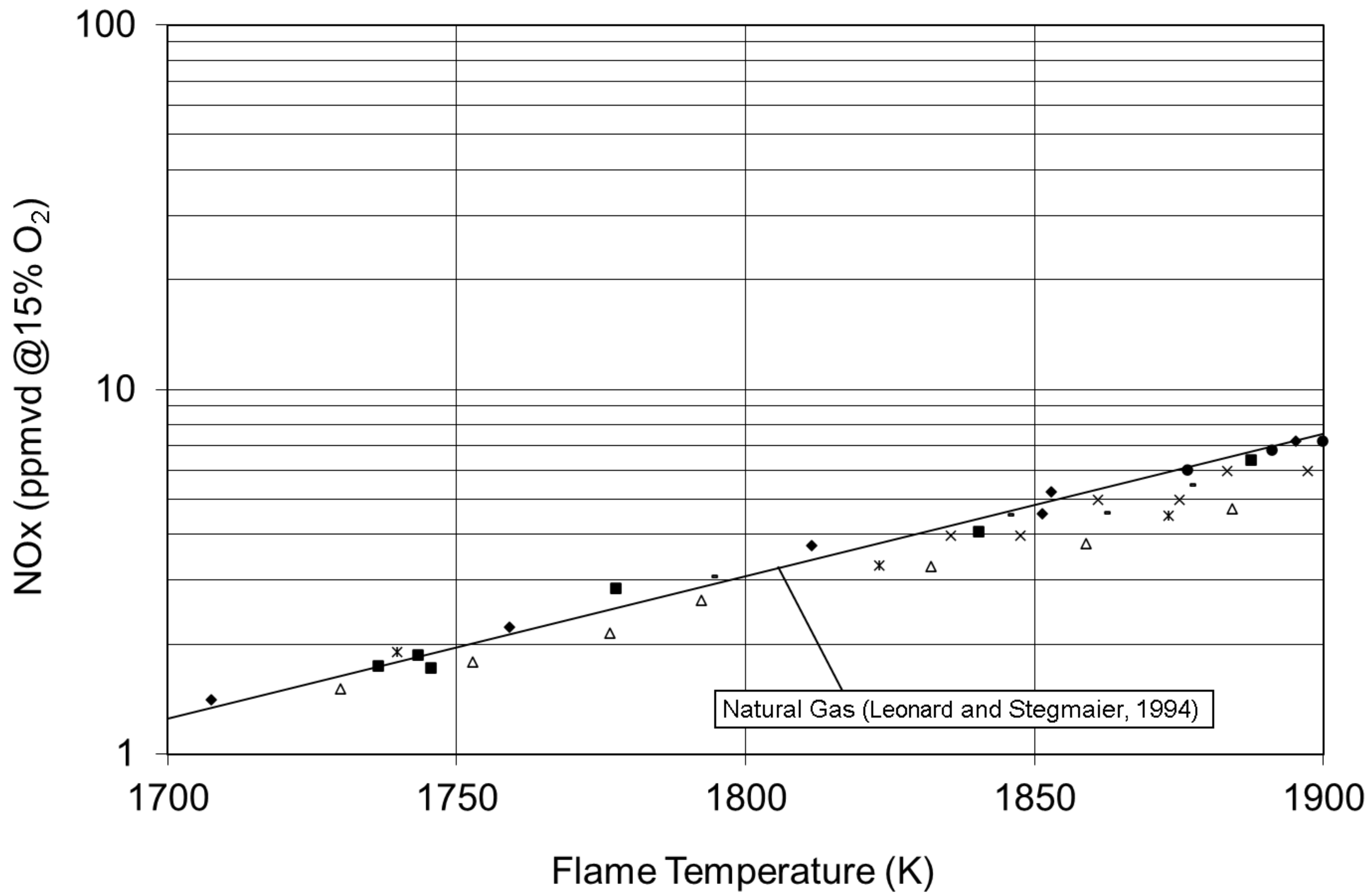
Tacina, R. (1990). Low NOx Potential of Gas Turbine Engines, Paper AIAA-90-0550, 28th Aerospace Sciences Meeting, Reno NV.



Data from: Dolan, B., Gomez, R., Zink, G., Pack, S., Gutmark, E., (2016). Effect of Nozzle Spacing on Nitrogen-Oxide Emissions and Lean Operability, AIAA Journal, Vol. 54(6), pp 1953-1961.

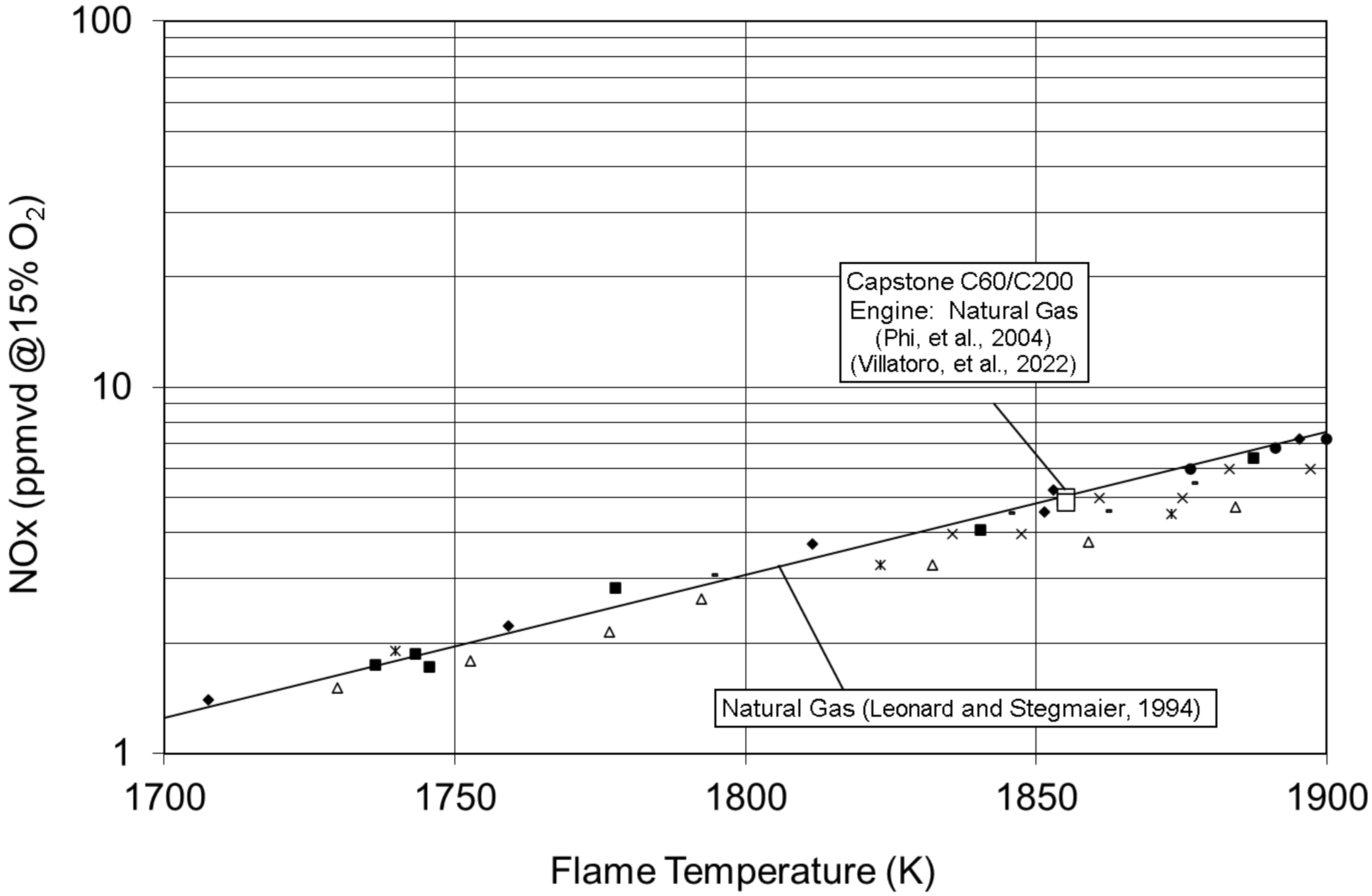
Prior Work

- **Industrial Engine Entitlement**



Prior Work

- **Industrial Engine Entitlement**



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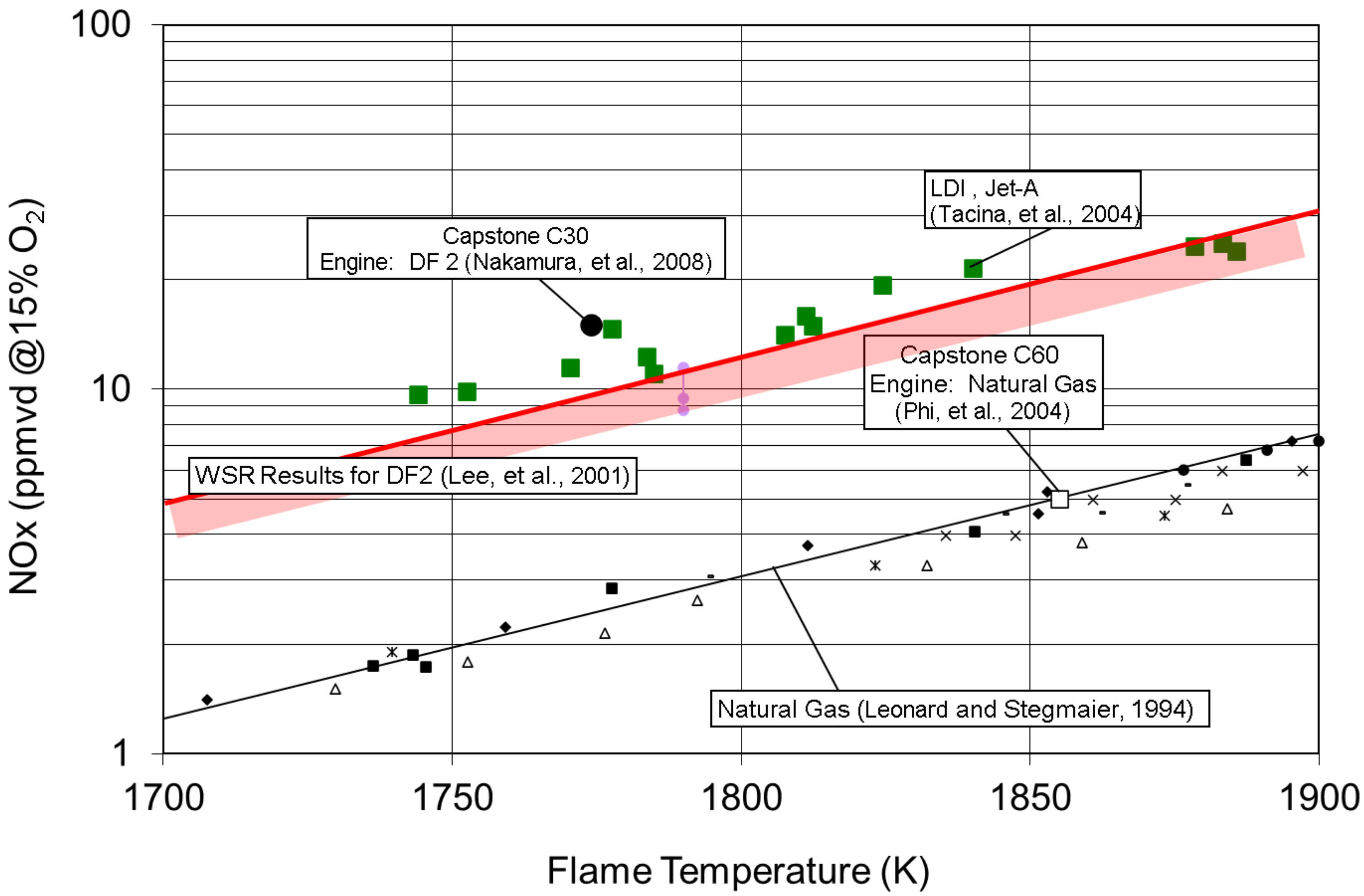
- **Industrial Engine Entitlement**



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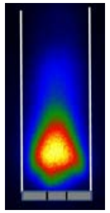
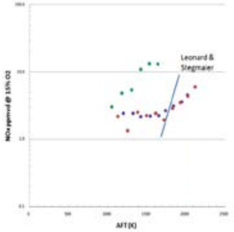
Objectives

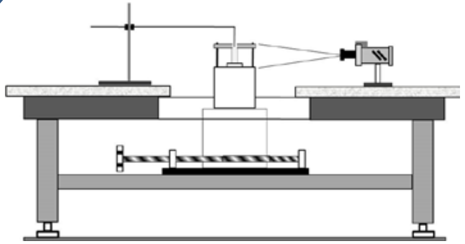
- **The proposed work will**
  - **1) <u>adapt</u> advanced LDI *liquid fuel injectors* designed by Collins Aerospace for aero engines to accommodate injection of hydrogen/hydrogen natural gas blends and <u>screen</u>**
  - **2) <u>demonstrate</u> their operation using experiments from laboratory scale model combustor configurations at elevated pressures and temperatures UC Irvine, and**
  - **3) develop a <u>design</u> for test hardware that can be demonstrated at engine conditions in a test rig demonstration at Solar Turbines.**

<u>Adapt</u>
Jet Fuel→Hydrogen

Screen

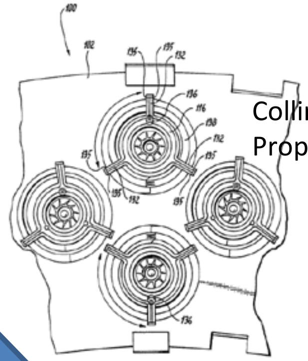


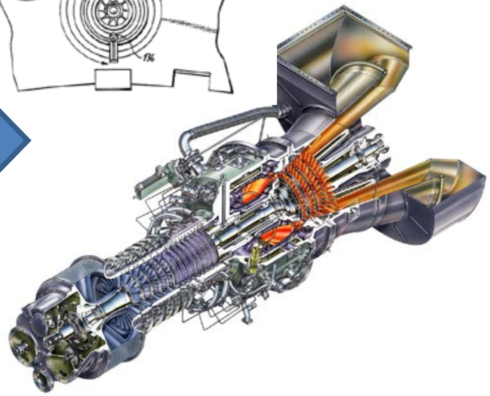




Demon-
strate

Design





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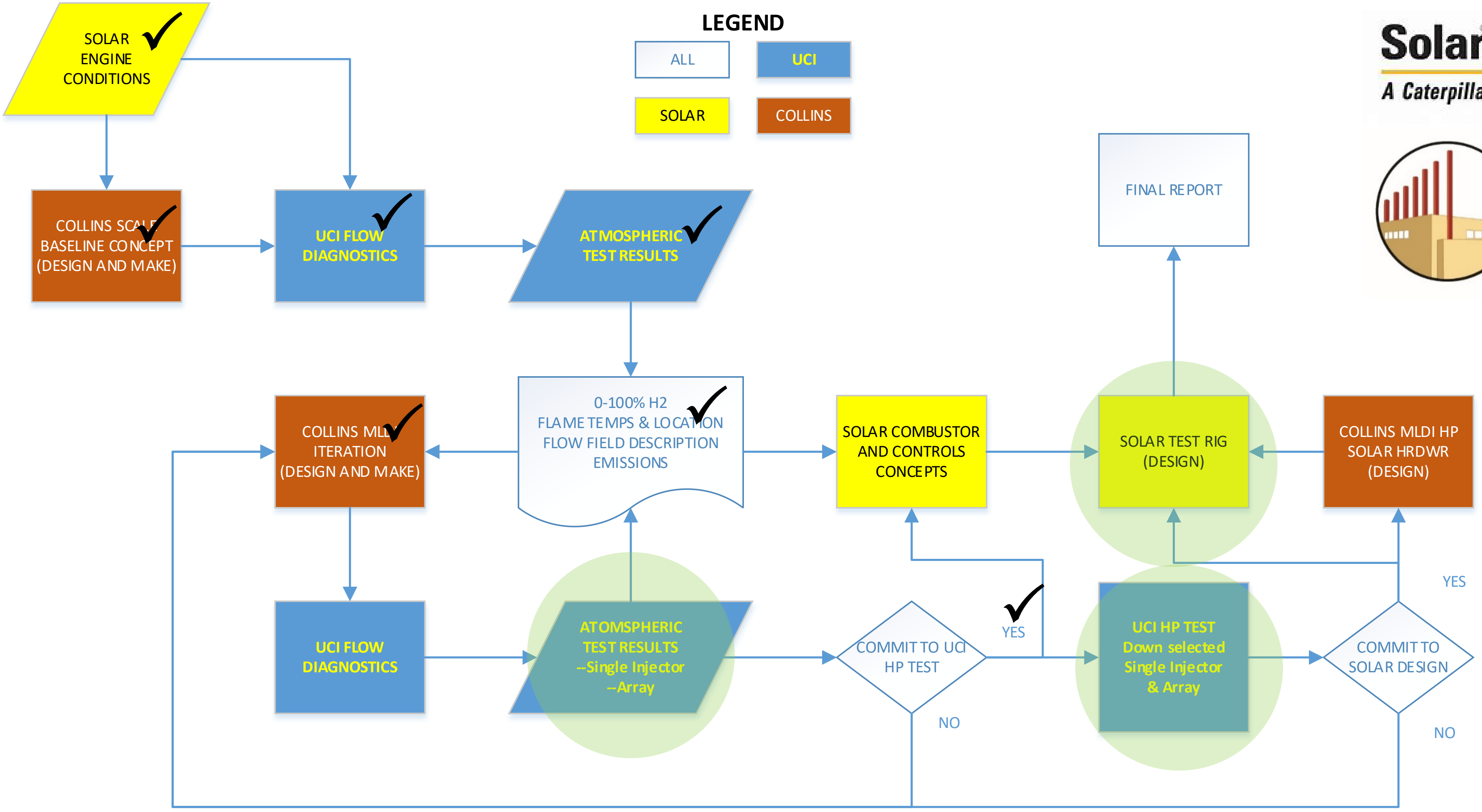
Technical Approach

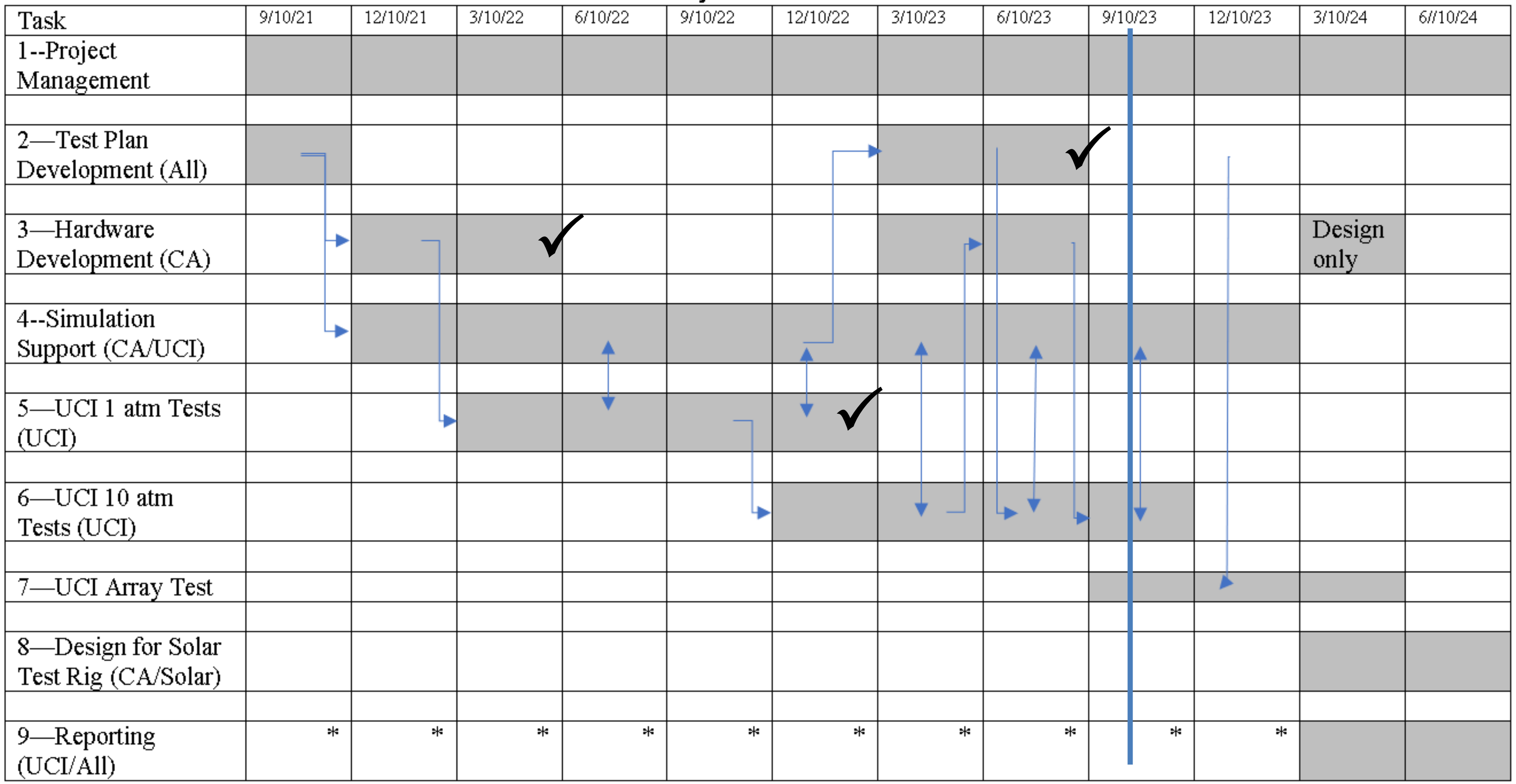
- **Team**



Schedule and Budget

DOE: $800,000
Cost Share: $200,000

Project Timeline

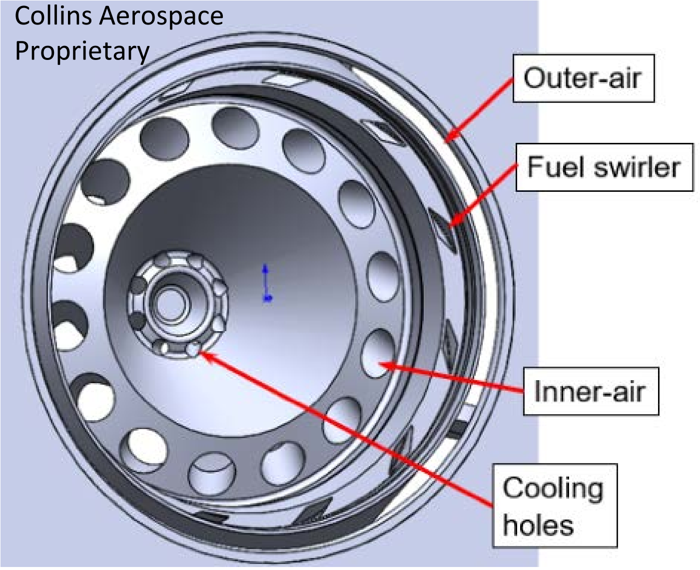


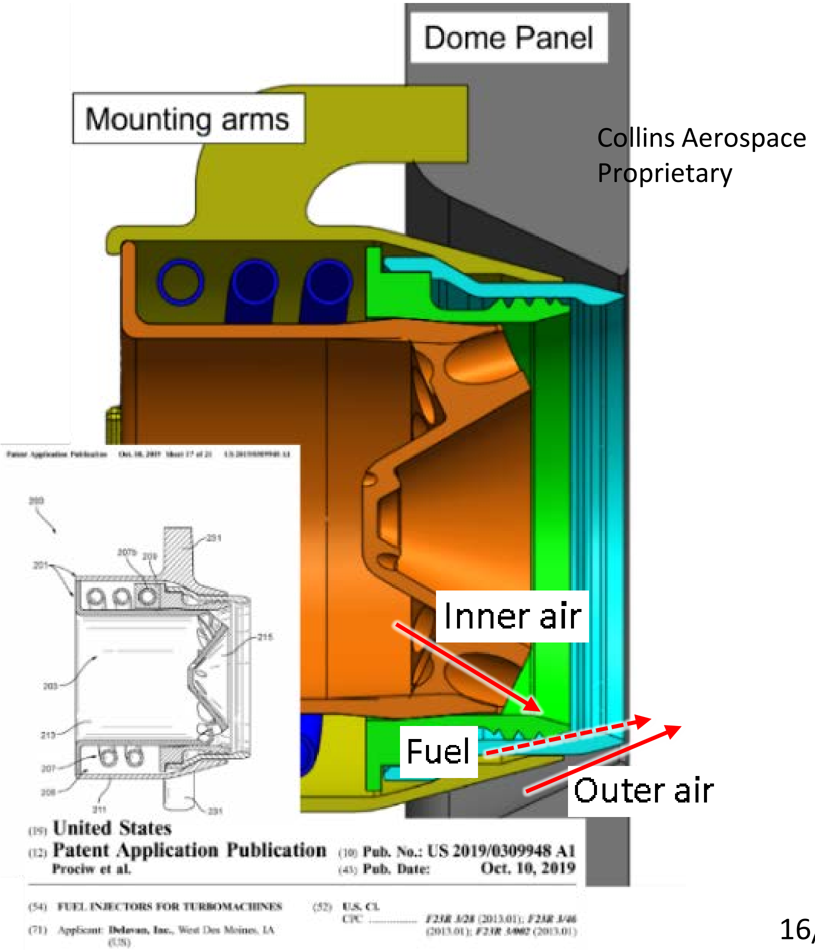
Milestones
--Test Plan Report ✓
--UCI Test Report—1 atm ✓
--UCI Test Report—10 atm
--Solar Design Report—Included in Final Report

--Quarterly Reports
--Final Report

Experimental methodology – CFD and Manufacturing

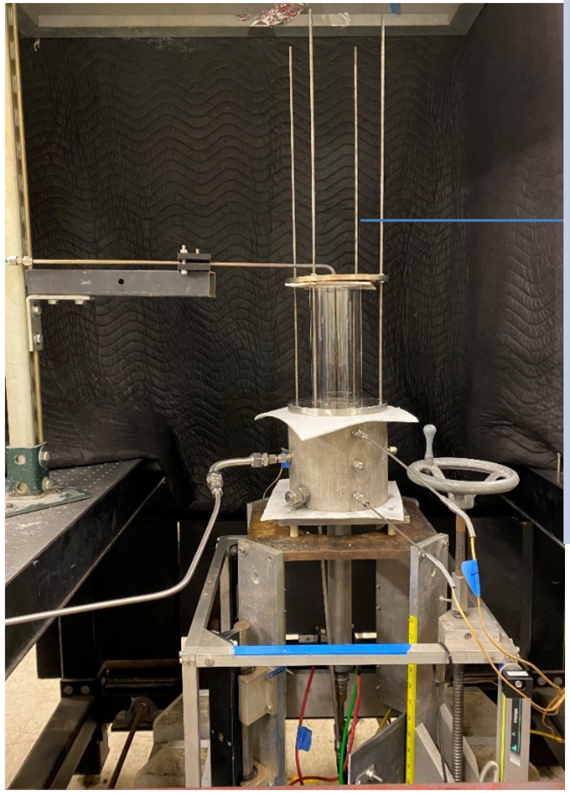
- **Design of Experiments to establish the geometry variations**
- **Computational Fluid Dynamics to size air and fuel circuits**
  - **Effective area targets: 0.145in^2 air, 0.0055in^2 fuel → expected 5-15% decrease for rough surface finish**
- **Additive manufacturing: Inconel 625**

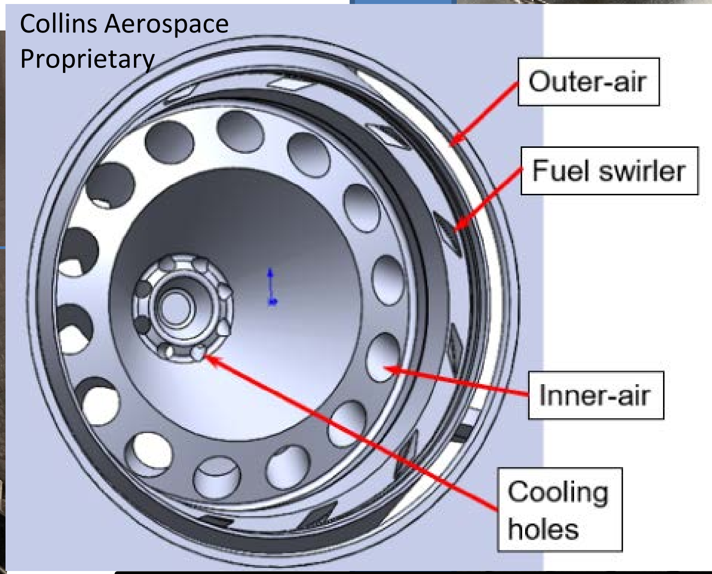


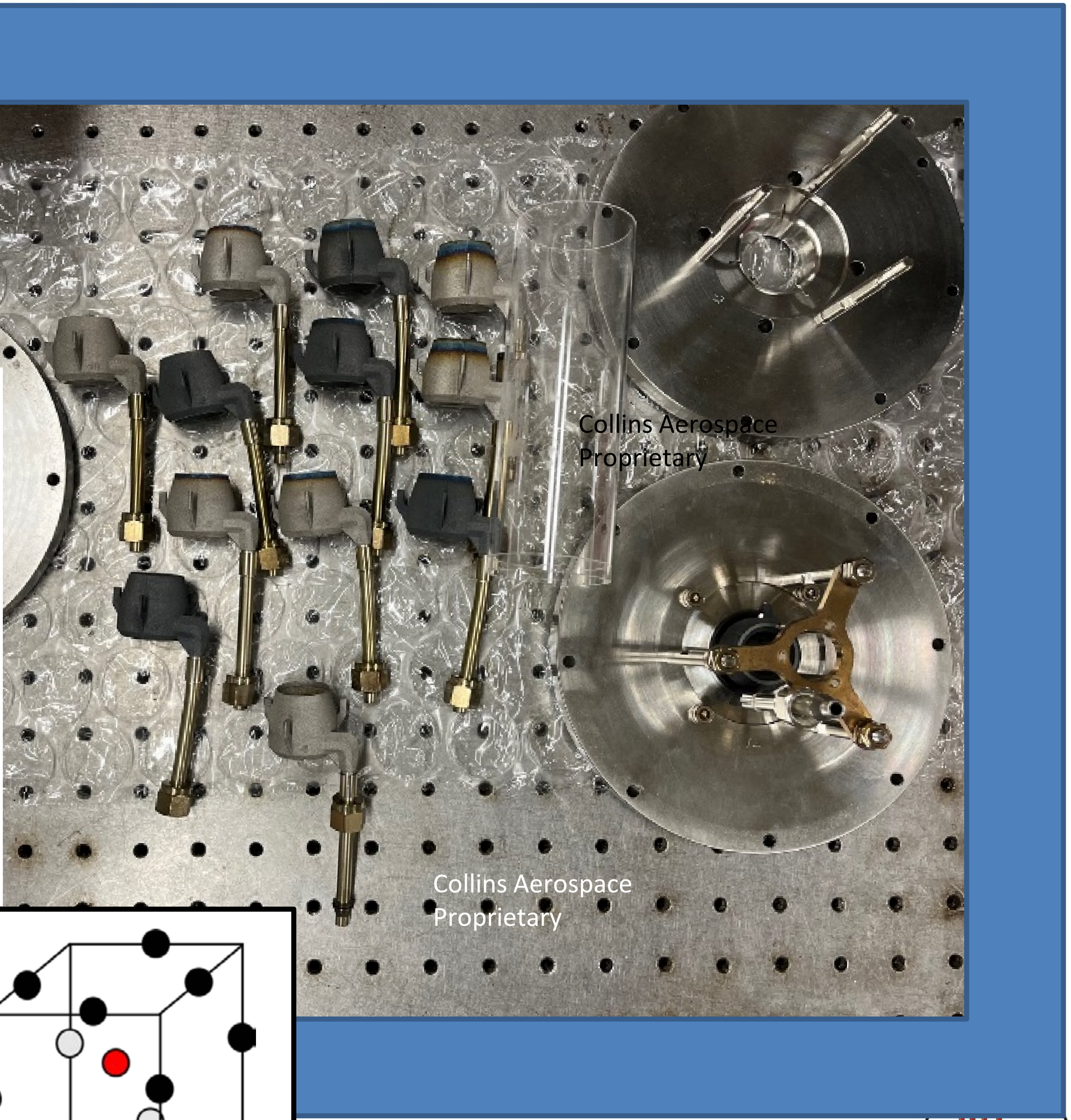


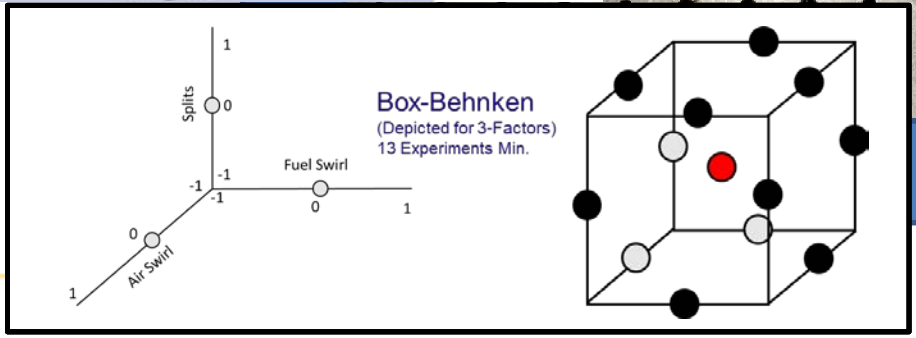
Injectors

- **As tested Collins injectors/ mounting plates**
  - **13 for pure B-B design**
  - **3 for correlation validation**





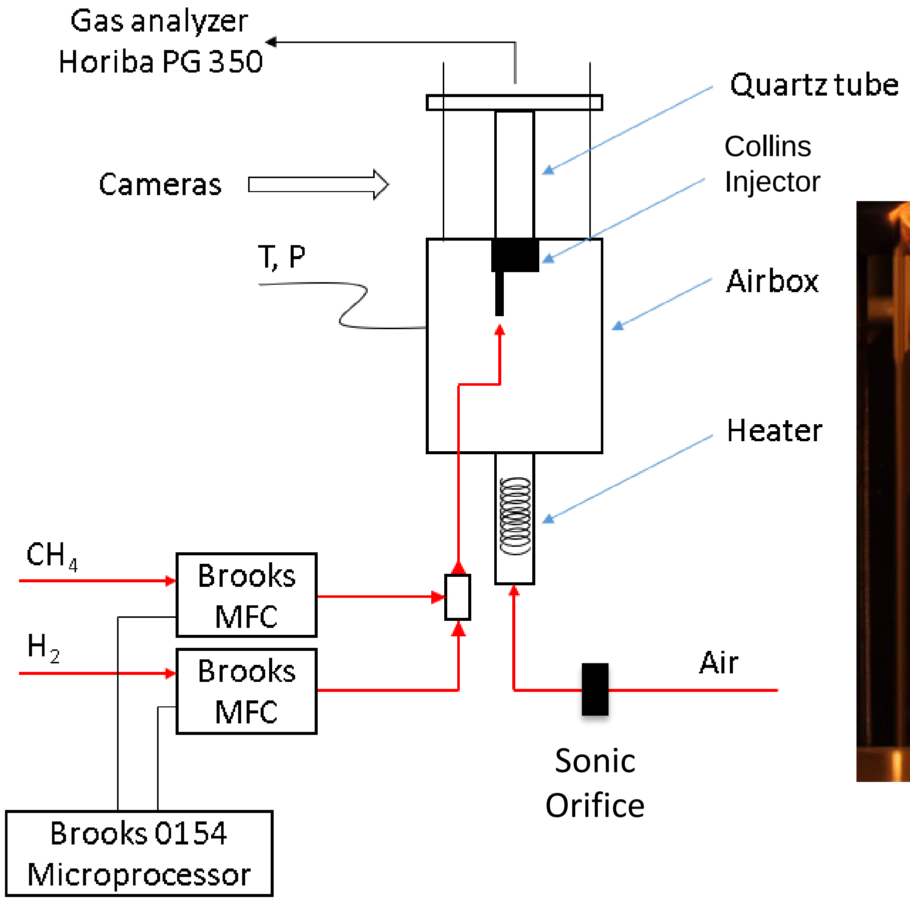




Experimental methodology – Experiment

- **13+3 injectors, with 3 different mounting plates**

- **6 kW Convectronics electric heater**
- **6in-long stainless steel airbox**
- **2x type K thermocouples**
- **Tek Bar 3120B pressure transducer**
- **3x Brooks 5000i Series Mass Flow Controllers**
- **Quartz tube combustor**
- **Horiba PG 350 gas analyzer (0.4 L/min)**
- **Nikon D90**
- **FB-N9-U Dynacolor**
- **Phantom v7.1**



Experimental methodology – Emissions

- **Horiba PG 350 gas analyzer (0.4 L/min)**
  - Exhaust well mixed in the radial at the exit (within 0.5 ppmvd)
  - Actual exhaust concentration represented by the centerline
- **Emissions for gas turbines: corrected to 15% O_2**
- **Bias when reporting H_2 vs CH_4 on a ppmvd basis**
  - ➔ EPA Method 19: ppmvd → ng/J

$$F_k = \frac{26854(3.64H + 1.53C + 0.57S + 0.14N - 0.46O)}{Q_{gr}}$$

$$S_m = S_{m,raw} F_k \frac{20.9}{20.9 - \%O_2}$$

$$F_{total} = \sum_{k=1}^{n} X_k F_k$$

Experimental methodology – Uncertainty

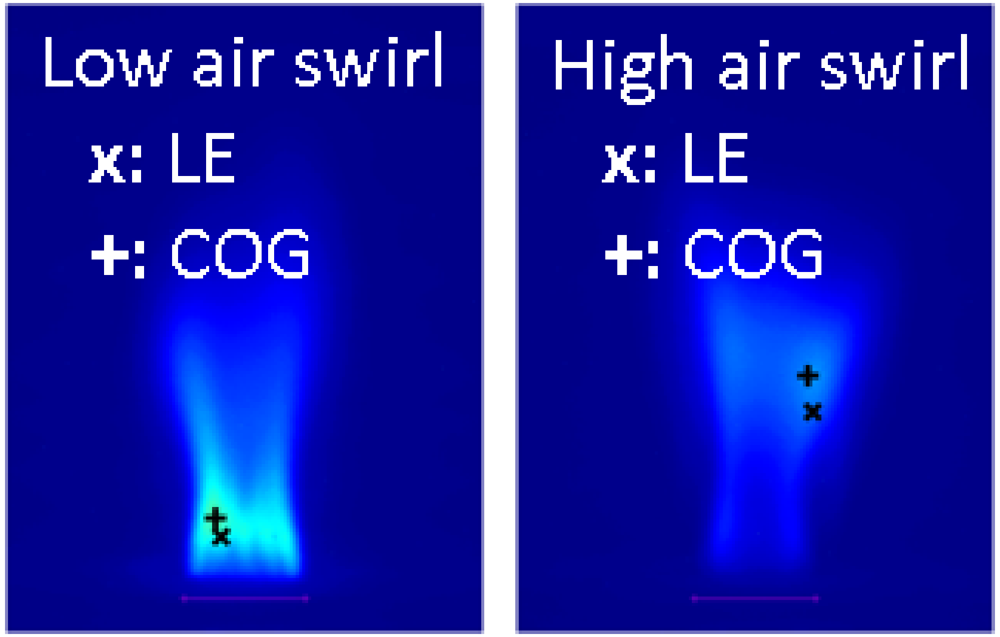
- Pressure transducers: $\pm$0.0075% full scale (145 psi, 5 psi)
- Brooks MFC: $\pm$1% full scale
- Heater controller: $\pm$2% of reading
- Temperature controller: $\pm$0.25% of reading
- Gas analyzer: $\pm$0.25% full scale (500 ppm CO, 50 ppm NO, 50 ppm NOx)

- Kline and McClintock accumulated uncertainty, partial derivatives of independent variables:
  - → Air effective area: 0.02%
  - → Fuel effective area: 3.91%
  - → Equivalence ratio at LBO: 6.68%
  - → Emissions: 11.1%

Experimental methodology – Flame diagnostics

- OH* chemiluminescence (as a flame marker)
  - Monochrome Dynacolor FB-N9-U – Sony CMOS sensor
  - Exposure time: 0.9999 s
  - Gain: 6 dB

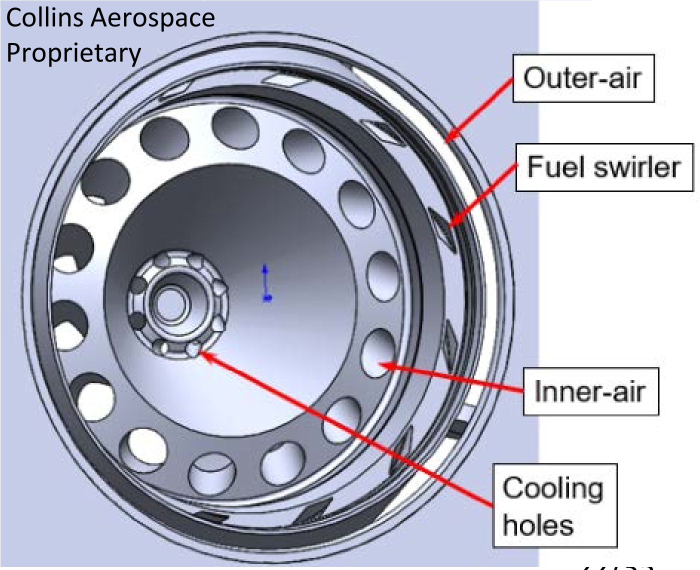
- MATLAB code to extract imaging responses
  - Average and Maximum brightness
  - Flame area and Heat release area (intensities >90% of max.)
  - Center of gravity (COG) and Leading edge (LE) of heat release area



Test Plan

- **LBO and EA: 15-point matrix for each injector: 12 from Box-Behnken + 3 repeats**

Factor	Low	Mid	High
A – Air Split	-1	0	1
B – Fuel Swirl	-1	0	1
C – Air Swirl (inner)	-1	0	1
D – Preheat Temperature [K]	465	573	675
E – Pressure Drop [%]	2	4	6
F – Fuel composition [% H_2] (by vol)	0	50	100



- **13 + 3 injectors**

- **Emissions: B-B 27 pt. (AFT > 1500K)**

  + 16 Low Temp Matrix (AFT <1500 K)

  → >600 test pts.

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Results

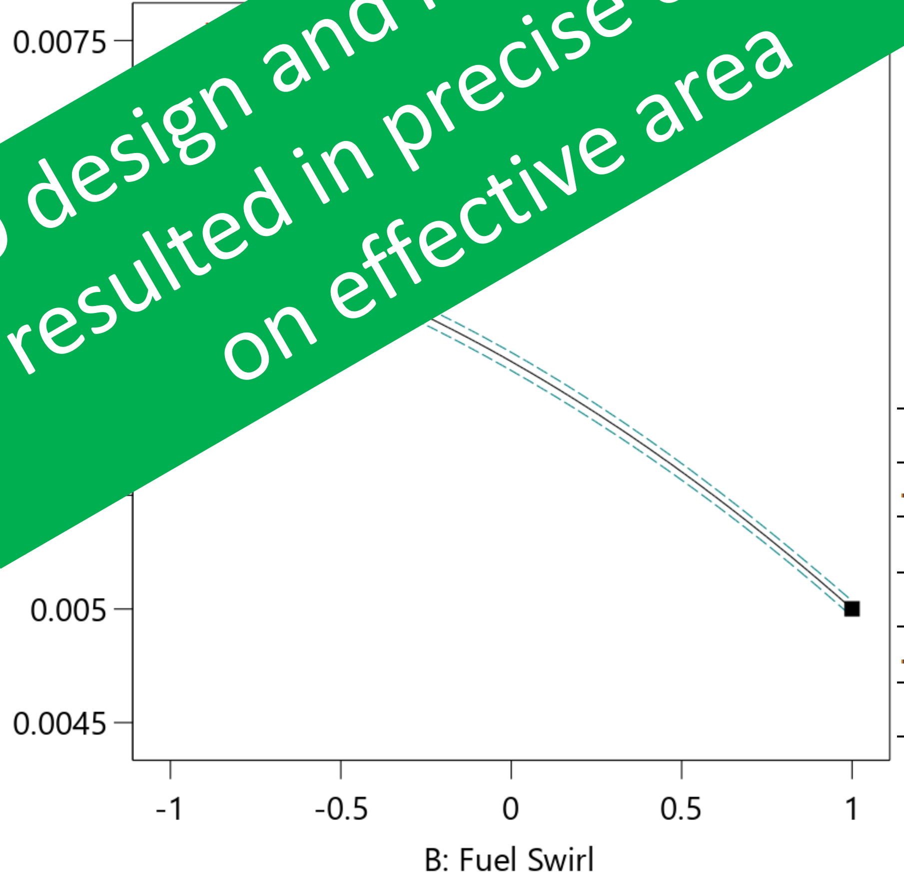
- Effective Areas
- Operability
- Emissions
- Imaging
- Optimization

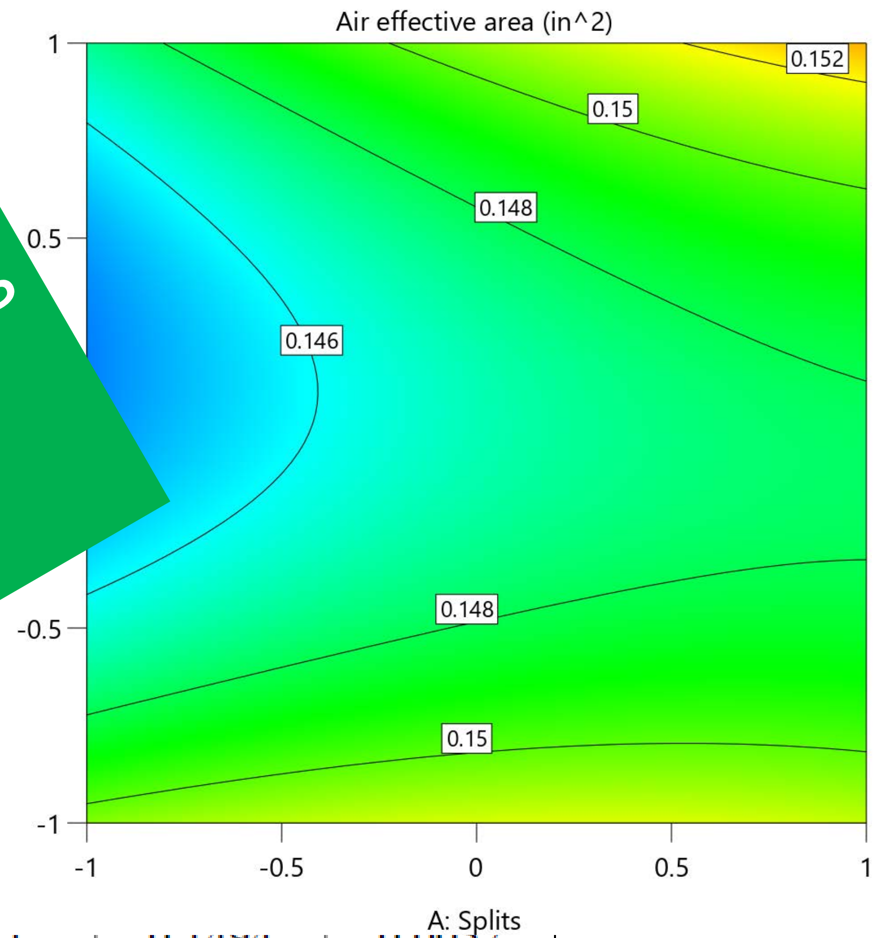
Results and discussion – Effective areas

- **Air circuit**
  - o **Average: 0.1492 in^2**
  - o **Std. dev.: 2.15 %**
- **Fuel circuit**
  - o **Average: 0.0058 in^2**
  - o **Std. dev.: 12.82 %**

Injector number	Air Split…	F…
1		

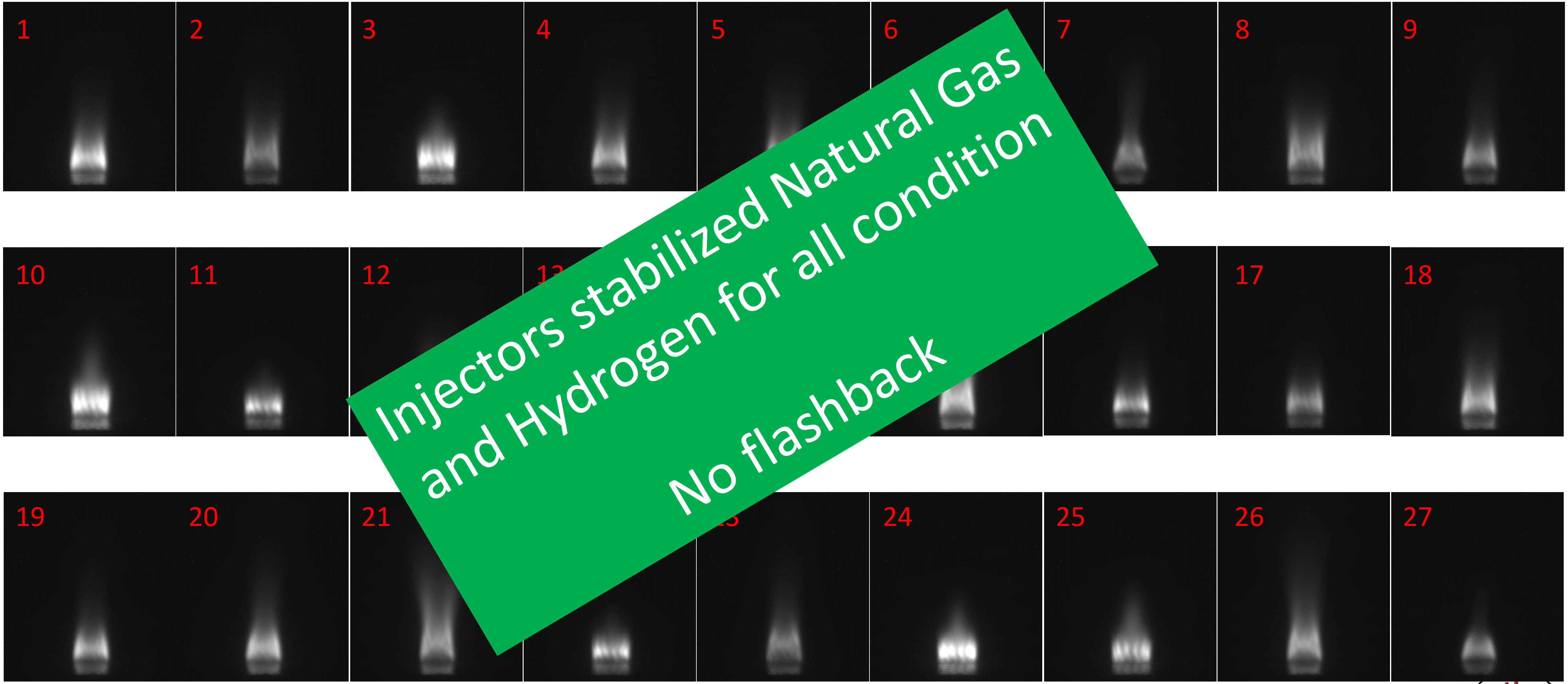
1	0.1494	0.0052
0	0.1429	0.0050
-1	0.1485	0.0061
0	0.1489	0.0071
1	0.1524	0.0051
-1	0.1484	0.0052
1	0.1456	0.0052





CFD design and manufacturing resulted in precise control on effective area

Flame Structure – OH* Dynacolor camera—Configuration 3—Example Results



Injectors stabilized Natural Gas and Hydrogen for all condition

No flashback

Results and discussion – Emissions

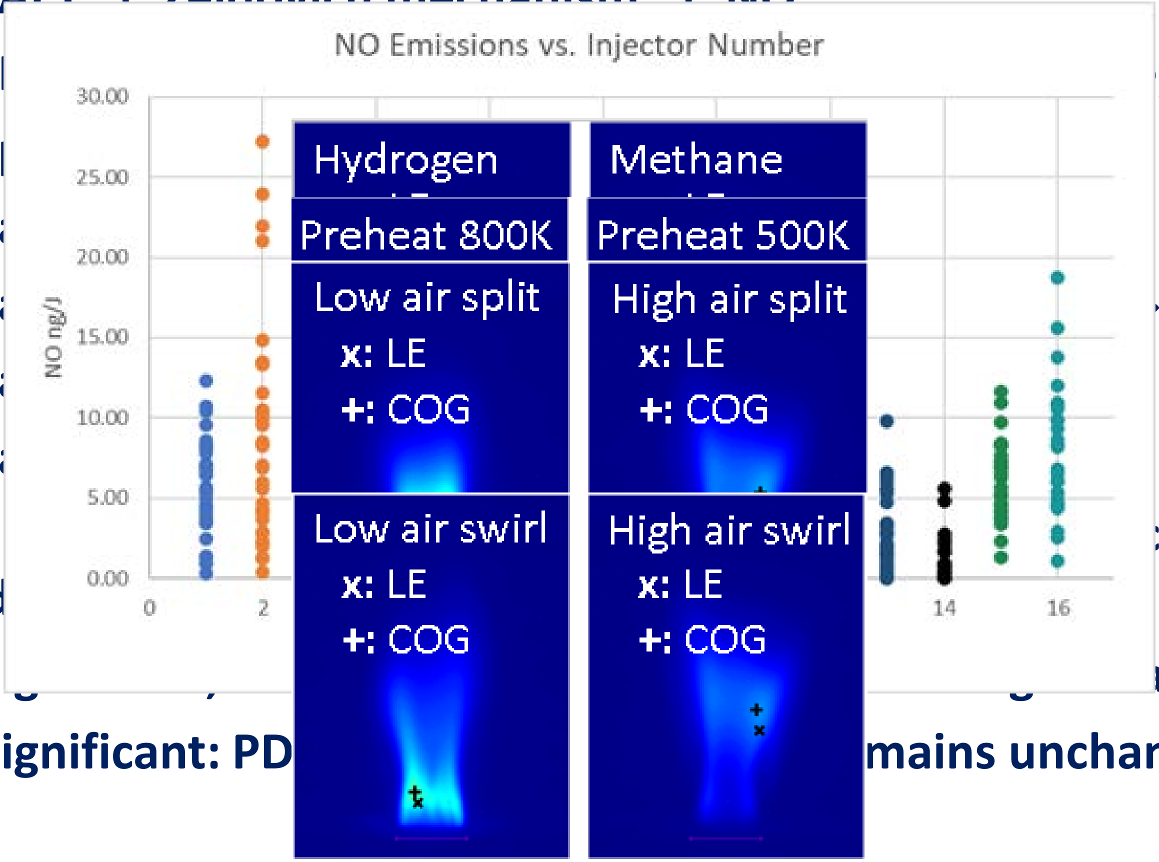
Factor
A – Air Split
B – Fuel Swirl
C – Air Swirl
D – Preheat Temperature [K]
E – Pressure Drop [%]
F – Fuel composition [% H_2] (by vol)

- **Analysis of Variance (ANOVA)**
  - **Significant if $p<0.05$**
  - **Simplification: term removed if change in C.V. within 5%**
- **Coded equations:**
  - $\ln(CO) = 2.56 - 0.1861A + 0.0456B - 0.3510C + 0.0925D - 0.0689E - 0.4942F - 0.8094G + 0.0535BC + 0.0957CG + 0.1299EF + 0.6036G^2$
  - $\sqrt{NO} = 2.10 - 0.3871A - 0.2834C + 0.4946E + 0.6395F + 0.4396G - 0.4104AC - 0.1711AF$
  - $\sqrt{NO_X} = 3.10 - 0.4204A - 0.2750C + 0.4810E + 0.4162F + 0.2095G - 0.4460AC - 0.1731AE + 0.1771AG + 0.1001CG$
- **Coefficient of Variance (C.V.): 8.81% for CO, 28.66% for NO, 15.90% for NOx**

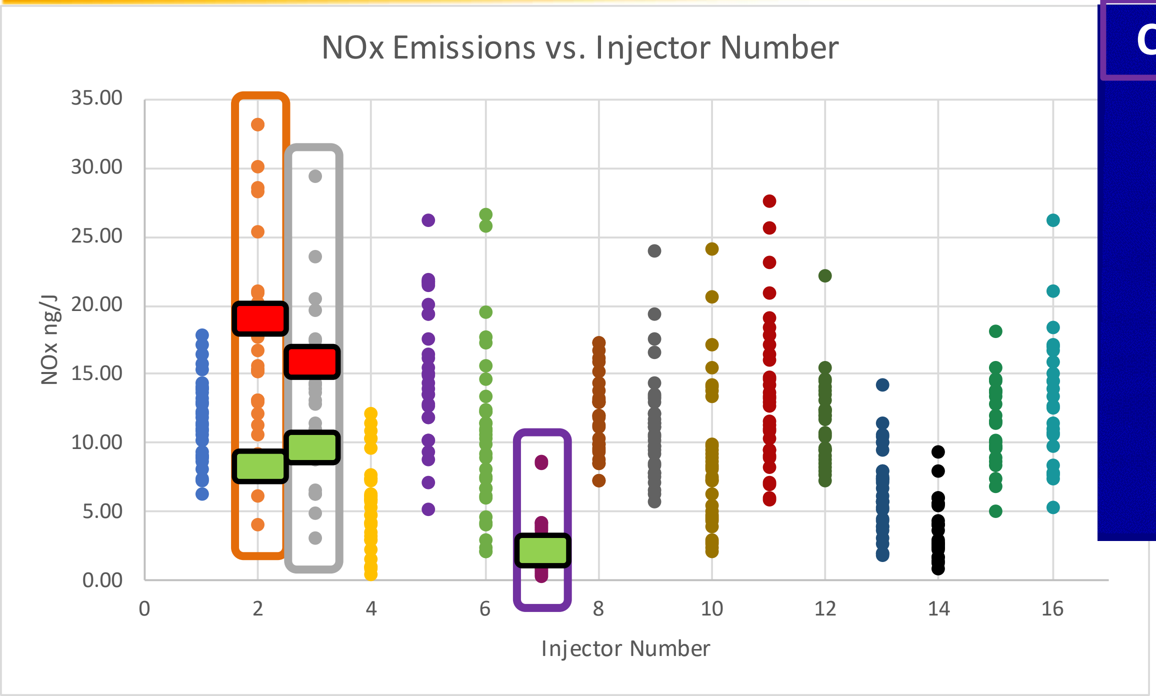
Results and discussion – NO model interpretation

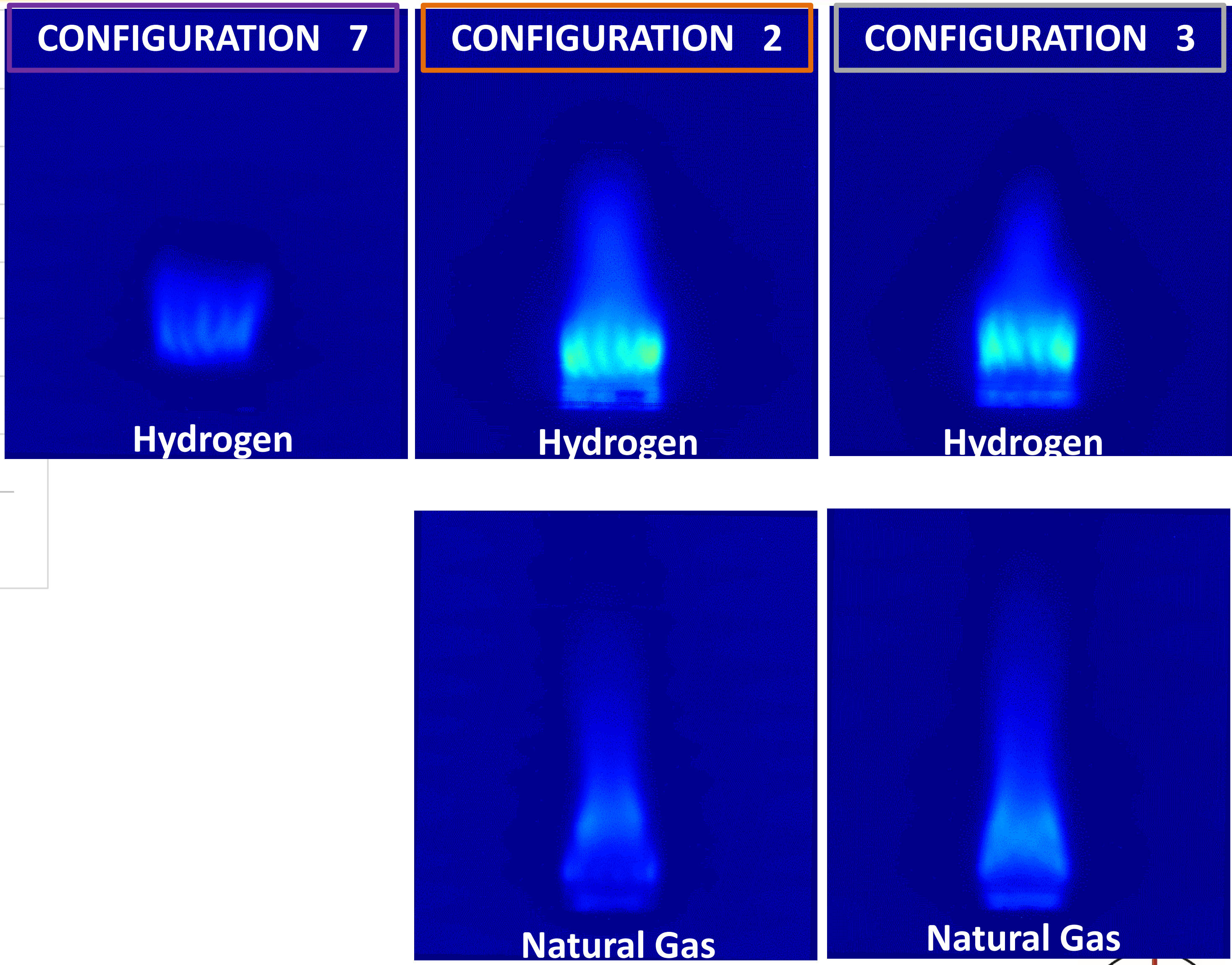
Factor
A – Air Split
B – Fuel Swirl
C – Air Swirl
D – Preheat Temperature [K]
E – Pressure Drop [%]
F – Fuel composition [% H_2] (by vol)

- $\sqrt{NO} = 2.10 - 0.3871A - 0.2834C + 0.4946E + 0.6395F + 0.4396G - 0.4104AC - 0.1711AF$
  - G, AFT: ↑ AFT, ↑ Zeldovich mechanism, ↑ NO
  - F, % H_2: ↑ … , ↑ NO
  - E, preheat: ↑ …
  - A, air split: ↑ …
  - AC: ↑ … NO
    ↓ …
  - C, air swirl: ↑ …
  - AF: air … creasing mixing, but ↑ H2 red…
  - B, fuel swirl: ins… an fuel flow rate
  - D, pressure drop: insignificant: PD … mains unchanged



Results and discussion – H2 vs CH4





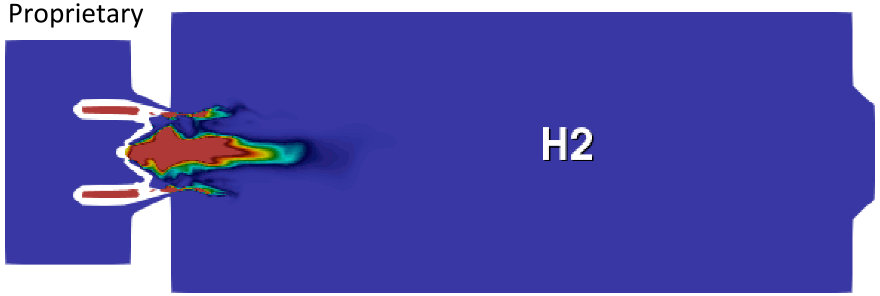
- **Pressure drop** **4%**
- **Preheat temperature** **675 K**
- **Adiabatic flame temp.** **1675 K**
- **NOx Hydrogen** **2.05/19.87/16.72**
- **NOx Natural gas** **---/9.31/10.19**

Example CFD—Collins Aerospace

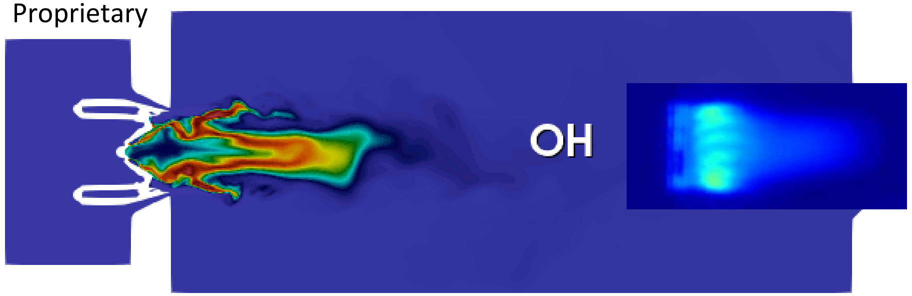
- **Relative Performance: Config 2 and Config 7**

Collins Aerospace Proprietary

Config-02, Hydrogen



Collins Aerospace Proprietary



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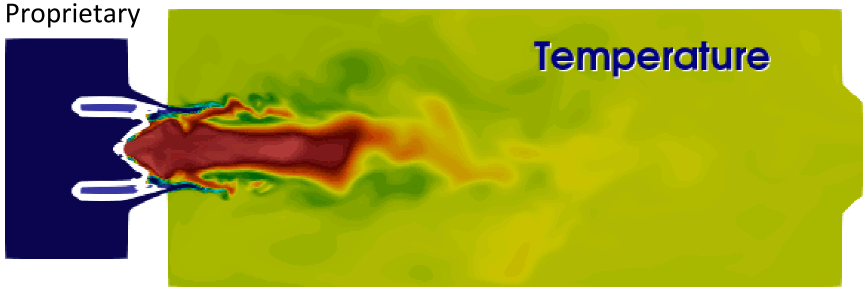

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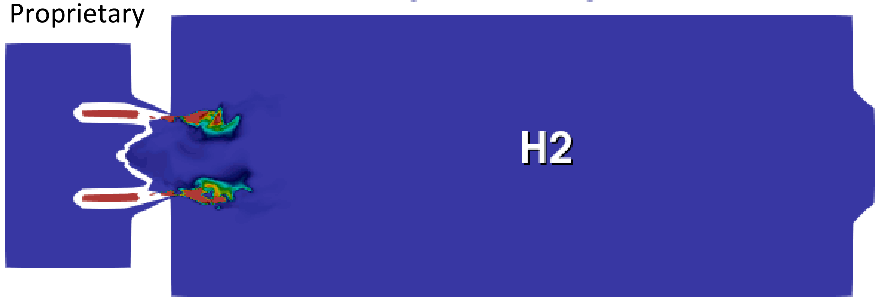
Config-07, Hydrogen



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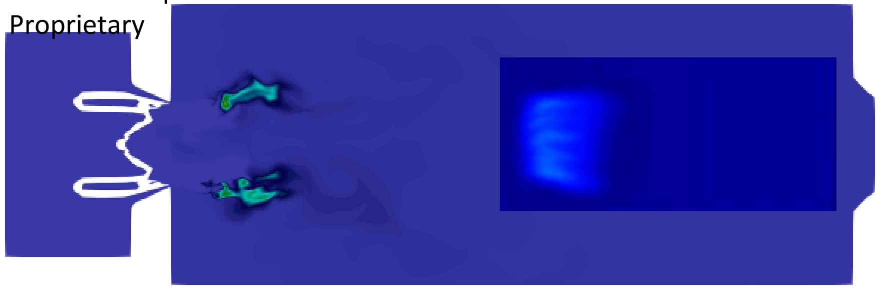

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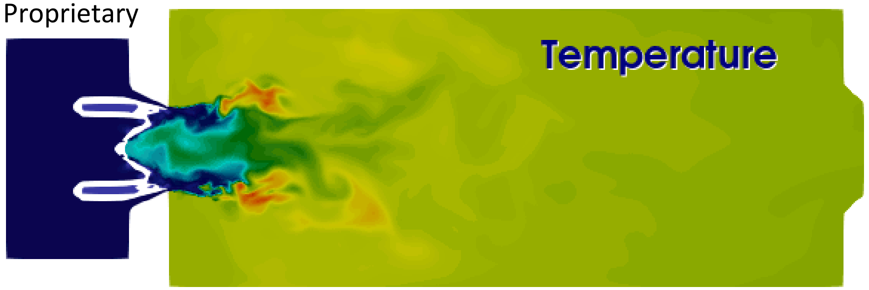


Results and discussion – Optimization

- Goal: minimization of CO, NO, and NOx, with low pressure drop
- Methane @ 675 K preheat

AFT [K]	Air Split	Fuel Swi[illegible]	[illegible]	[illegible]	NO [ng/J]	NOx [ng/J]
1500	1	[illegible]	[illegible]	[illegible]	0.36	1.87
1675	1	[illegible]	[illegible]	[illegible]	1.09	3.43
1850	[illegible]	[illegible]	[illegible]	[illegible]	2.19	5.47

Single digit NOx attained

Optimization leads to 2^{nd} set of hardware for final tests

- Hydrogen @ 67[illegible]

A[illegible]	[illegible]	[illegible]	[illegible] Swirl	P.D. [%]	NO [ng/J]	NOx [ng/J]
15[illegible]	[illegible]	[illegible]	1	2.01	2.37	4.83
1675	[illegible]	0.44	1	2.00	3.91	7.20
1850	[illegible]	0.09	1	2.00	5.84	10.05

- ↑ air split and ↑ air swirl are preferred
- ↓ fuel swirl preferred for fuel flexibility performance

Outline

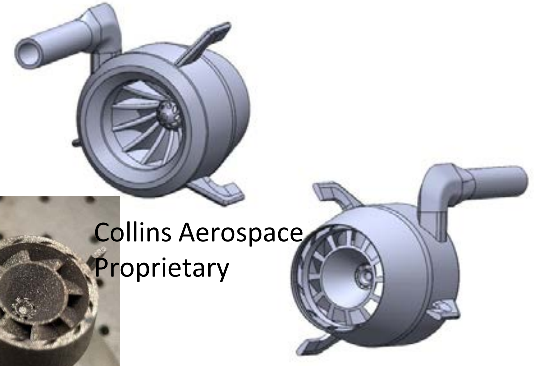
- Background
- Project objective(s)
- Technical approach
  - Team
  - Tasks
  - Schedule
- Results/Conclusions
- Next Steps

Conclusions

- CO is decreased with: ↑ AFT, ↑ air swirl, ↑ H_2, ↑ air split
- NO is decreased with: ↑ air split, ↑ air swirl, ↓ preheat
- NOx is 60-80% NO
  - Traditionally 90-95%...
- Optimization
  - Injector and emissions levels not sensitive to flame temperature, preheat and fuel composition
  - New injector configuration with: +1 air split, -1 fuel swirl, +1 air swirl
- Best-case scenario: ↑ air split, ↑ air swirl, ↓ preheat, ↓ AFT
- Average lowest emissions are 1.54 and 1.67 ng/J (0.8 and 1.27 ppmvd 15% O_2) for methane and hydrogen, respectively
  - NOx Entitlement for jet fuel attained with pure hydrogen combustion.

Next Steps

- **Based on optimization, new configs designed/manufactured that should further reduce NOx**



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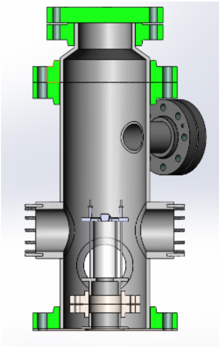
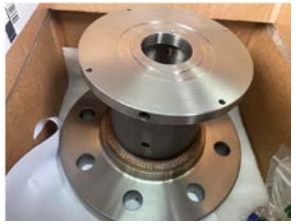
- **Test single injectors at high pressure**
- **Premixed configuration for baseline**
    - **See Malcolm Overbaugh Poster**





- **Array Testing**
- **Continued analysis**

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- **Collins Aerospace**
  - **Ottavio De Beni**
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  - **Brandon Williams**
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Adaptation of Aeroengine Micromixing Injectors for Lean Direct Injection of Hydrogen and Hydrogen/Natural Gas Blend (2023). **GT2023-101577** ASME TurboExpo 2023 (I. Escudero, B. Tran, M. Overbaugh, V. McDonell, B. Williams, P. Buelow, J. Ryon, O. De Beni)

Emissions and Flame Structure Assessment of Aeroengine Micromixing Injectors for Lean Direct Injection of Hydrogen and Hydrogen/Natural Gas Blends (2023). **GT2023-102632,** ASME TurboExpo 2023 (B. Tran, I. Escudero, V. McDonell