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

DE-FE0032073

2024 UTSR Workshop
24-25 September 2024
Tuscaloosa, Alabama

Katelyn Ballard and Matt Adams, Technical Monitors

UCI Combustion Laboratory
UCIrvine | University of California

Solar Turbines
A Caterpillar Company

Collins Aerospace

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24 September 2024
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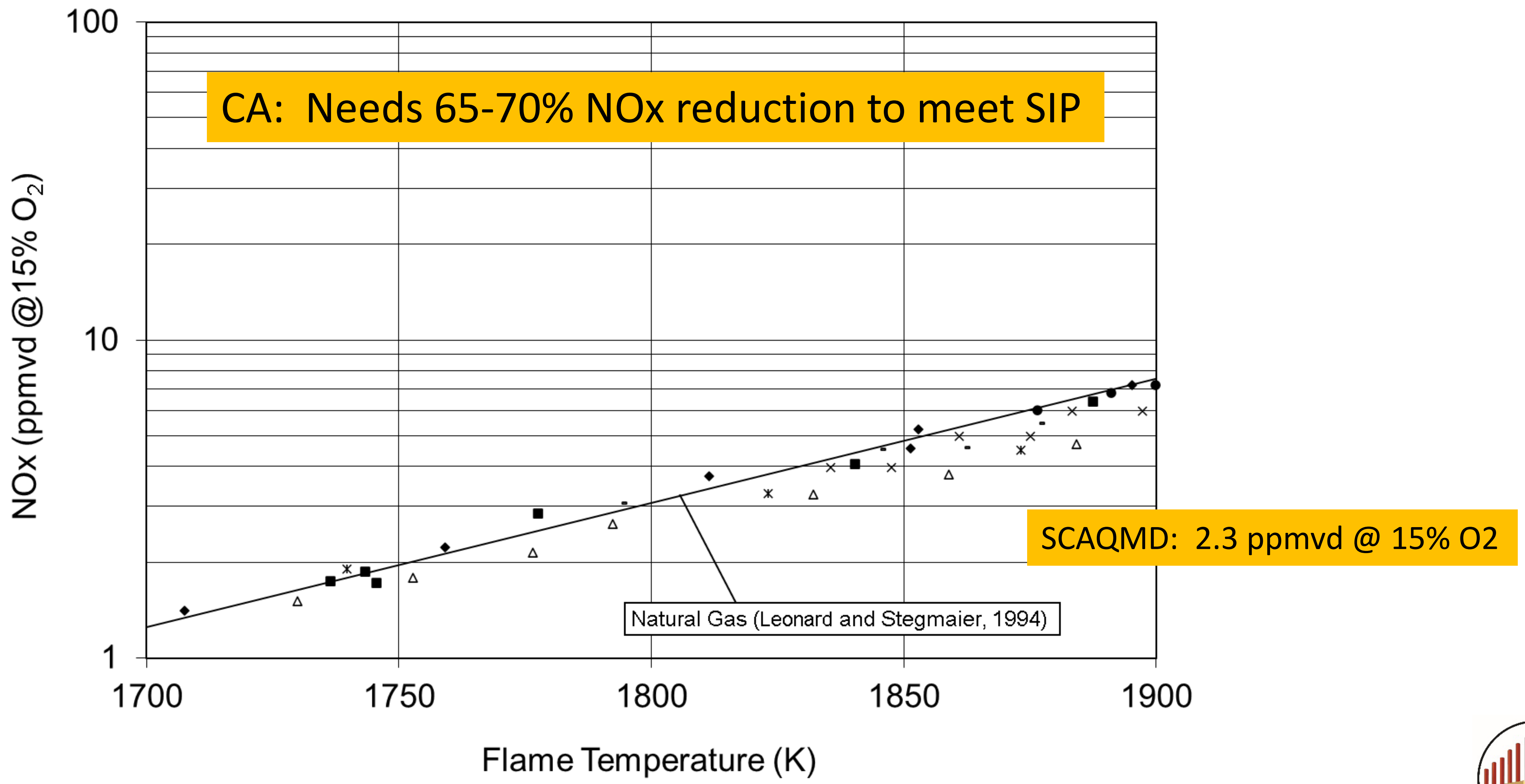
Outline

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

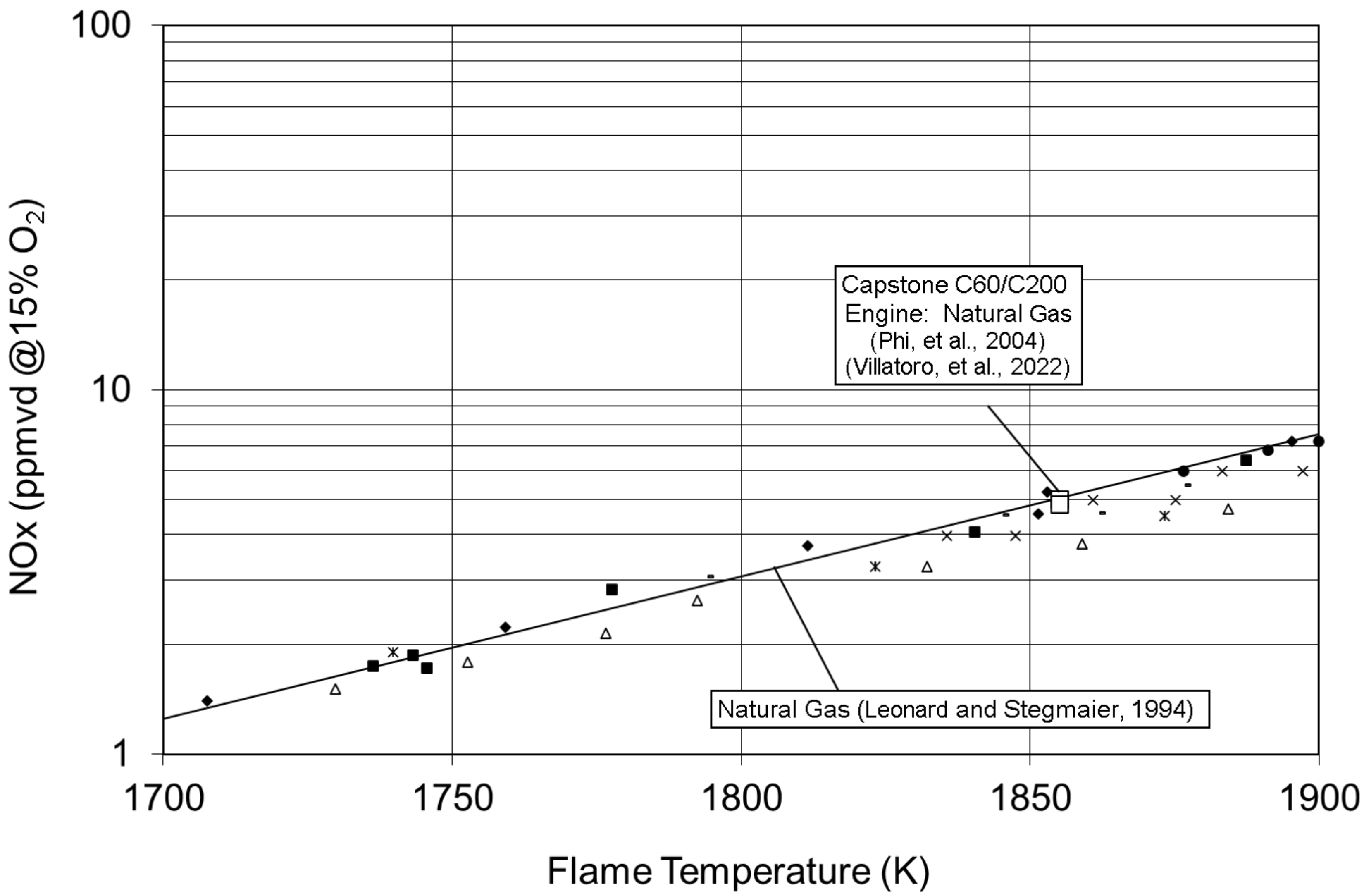
Background

- **Decarbonization is important, but Air Quality is also vital**



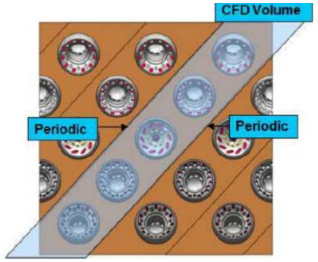
Background

- **Entitlement NOx can be attained on DLN commercial products**

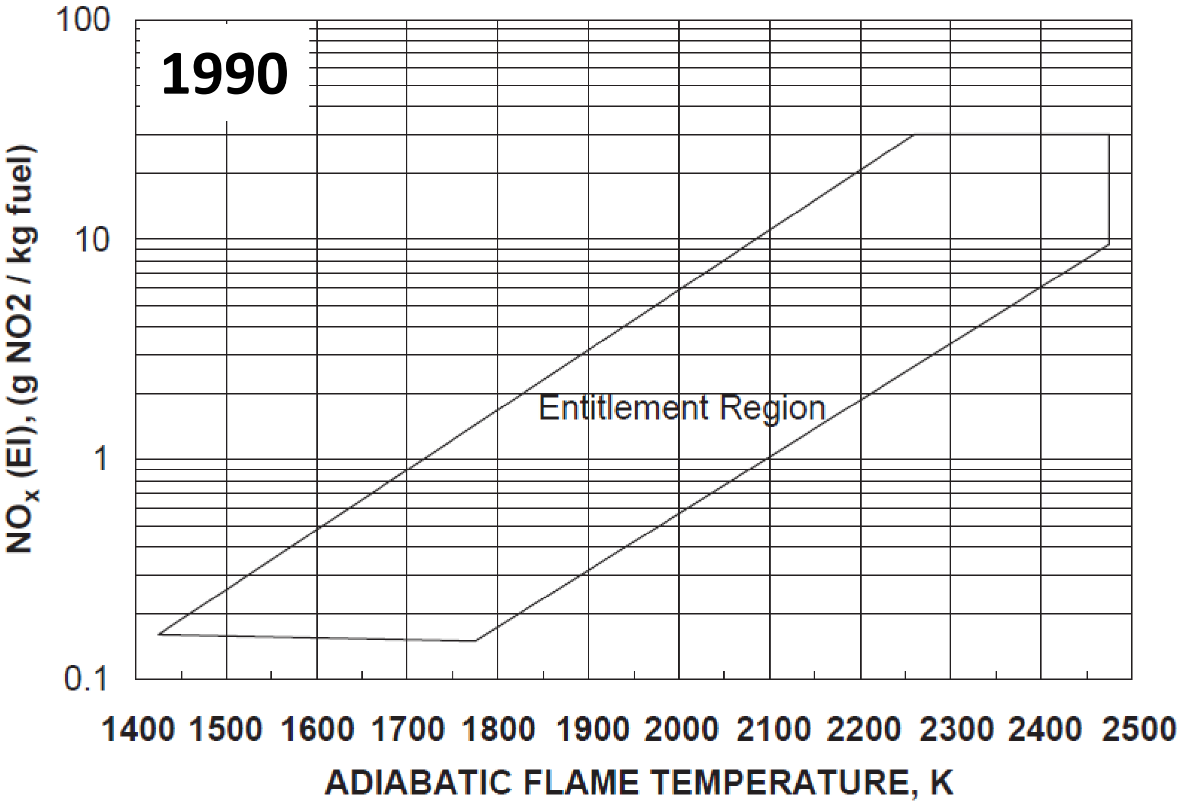


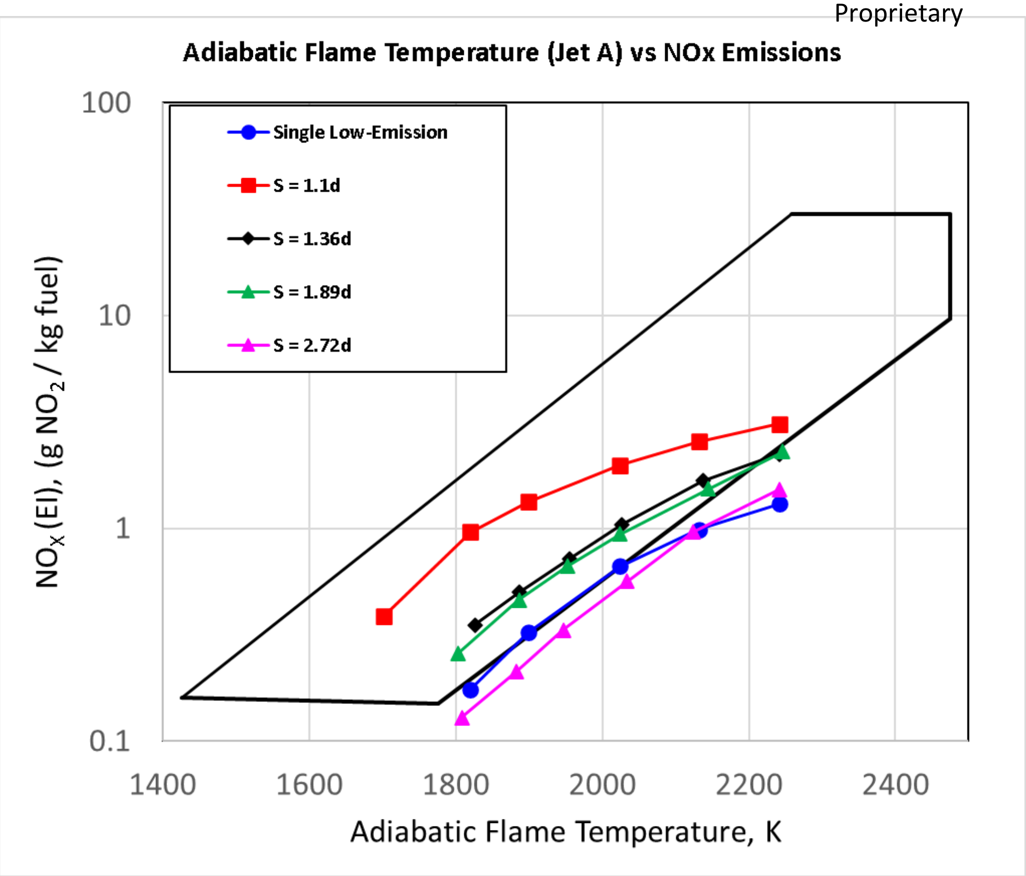
Background

- **LDI Injectors can attain entitlement emissions for Jet-A**
  - **Example: Collins Aerospace LDI concept**



Collins Aerospace Proprietary



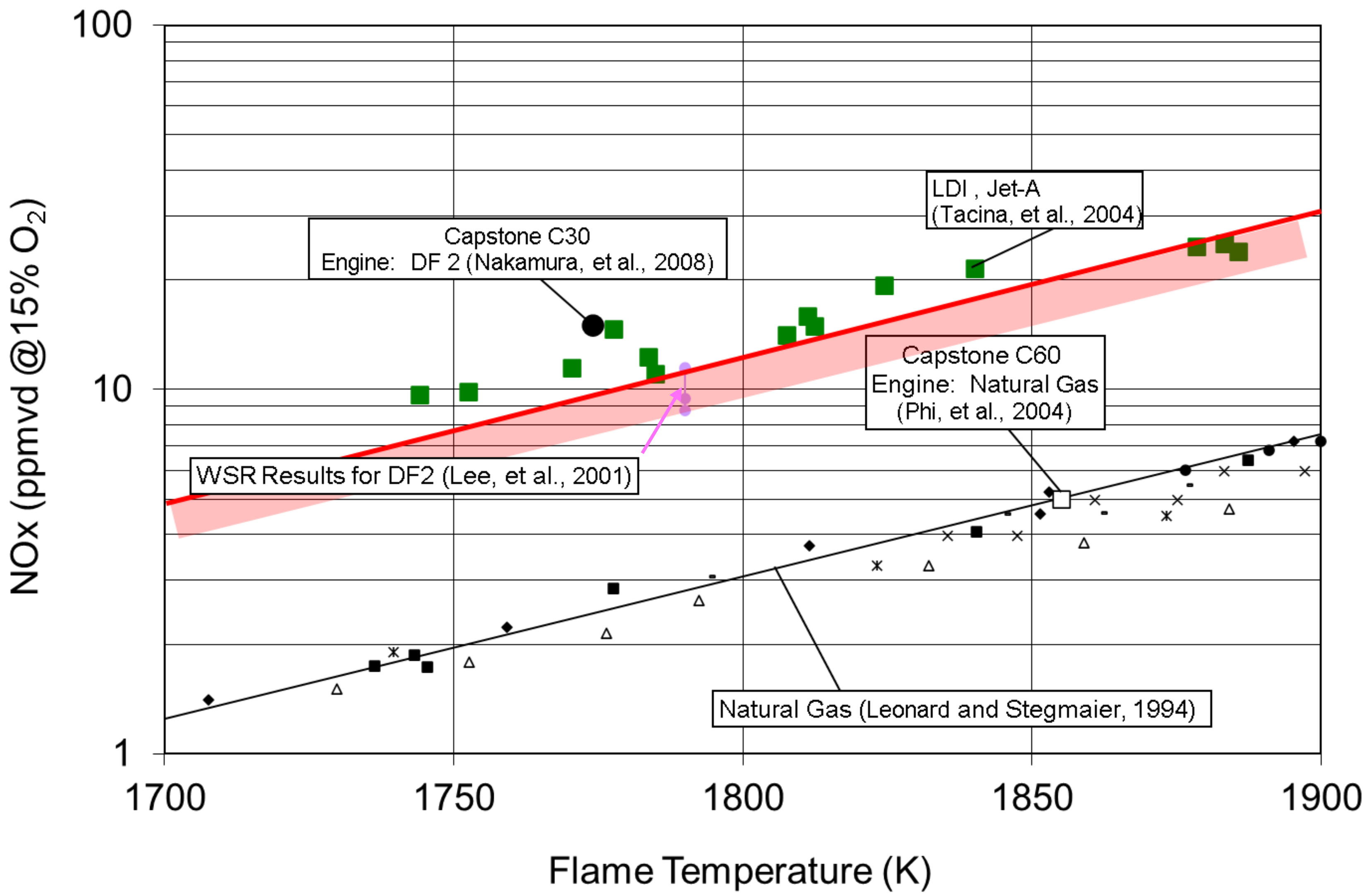


Tacina, R. (1990). Low NOx Potential of Gas Turbine Engines, Paper AIAA-90-0550, 28th Aerospace Sciences Meeting, Reno NV.

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.

Background

- **Industrial Engine Entitlement**
  - **Fuel Dependent!**
    - ✓ **Liquid fuel ~5x NG**
    - ✓ **H2?**



Background

- **Reactivity: H_2 vs CH_4 vs Jet-A**
  - Flashback a risk for H_2 (and Jet-A)
    - ✓ Short chemical time
    - ✓ High relative flame speed (e.g., laminar at phi ~ 0.7)
      - CH4: X
      - Jet-A: 4X
      - H2: 10X
    - ✓ Pressure exacerbates the issue
      - τ_{chem} reaches minimum ~10 bar
  - Autoignition a major risk for Jet-A
    - ✓ Avoid premixing!
- **LDI concepts have been successful for difficult operability cases and able to attain low emissions**

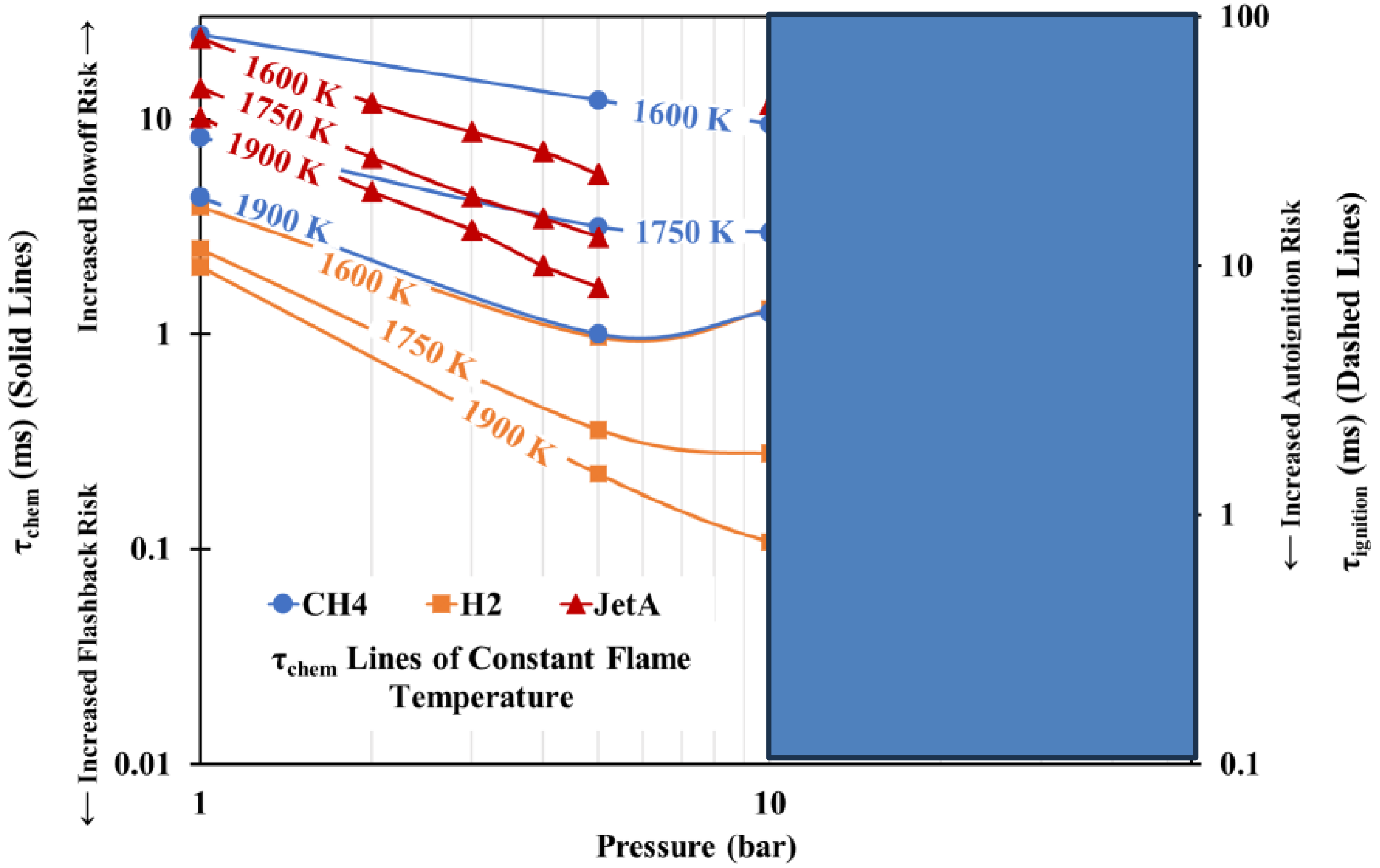


Fig. 7: Chemical time scale (α/s_L^2) and autoignition time for different fuels. CH_4 and H_2 data generated from GRI-Mech 3.0 [18]. Jet-A data generated from HyChem A2 mechanism [19, 20].

Lieuwen, et al. (2024). Roles for combustion and combustion R&D in a decarbonized world, Proceedings, 40th Symposium (International) on Combustion.

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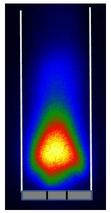
Objectives

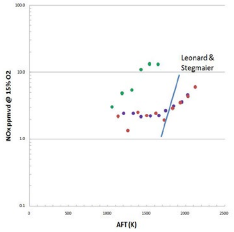
- **The proposed work will**
  - **1) <u>adapt</u> advanced LDI *liquid fuel injectors* designed by Collins Aerospace for Jet-A fueled aero engines to accommodate injection of hydrogen/hydrogen natural gas blends and <u>screen</u>**
  - **2) <u>demonstrate</u> their operation using experiments from laboratory 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**

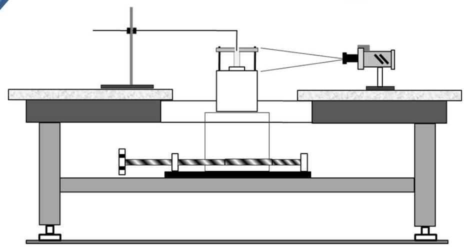
<u>Adapt</u>

Jet Fuel→Hydrogen

Screen

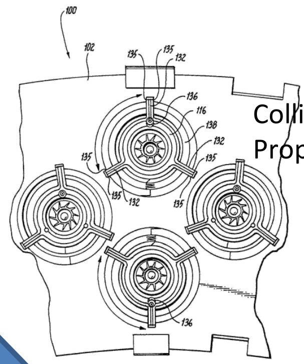




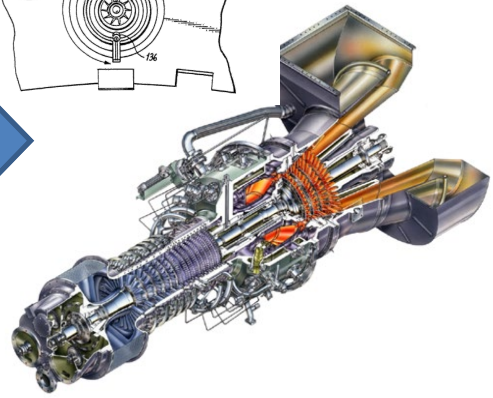


Demo

Design



Collins Aerospace Proprietary



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    - Tasks
    - Schedule
- Results/Conclusions
- Next Steps

Tasks and Schedule

Project Timeline

Task	9/10/21	12/10/21	3/10/22	6/10/22	9/10/22	12/10/22	3/10/23	6/10/23	9/10/23	12/10/23	3/10/24	6//10/24	9/10/24	12/10/24
1--Project Management														
2—Test Plan Development (All)														
3—Hardware Development (CA)														
4--Simulation Support (CA/UCI)														
5—UCI 1 atm Tests (UCI)														
6—UCI 10 atm Tests (UCI)														
7—UCI Array Test														
8—Design for Solar Test Rig (CA/Solar)														
9—Reporting (UCI/All)	*	*	*	*	*	*	*	*	*	*	*	*	*	*

DOE: $800,000

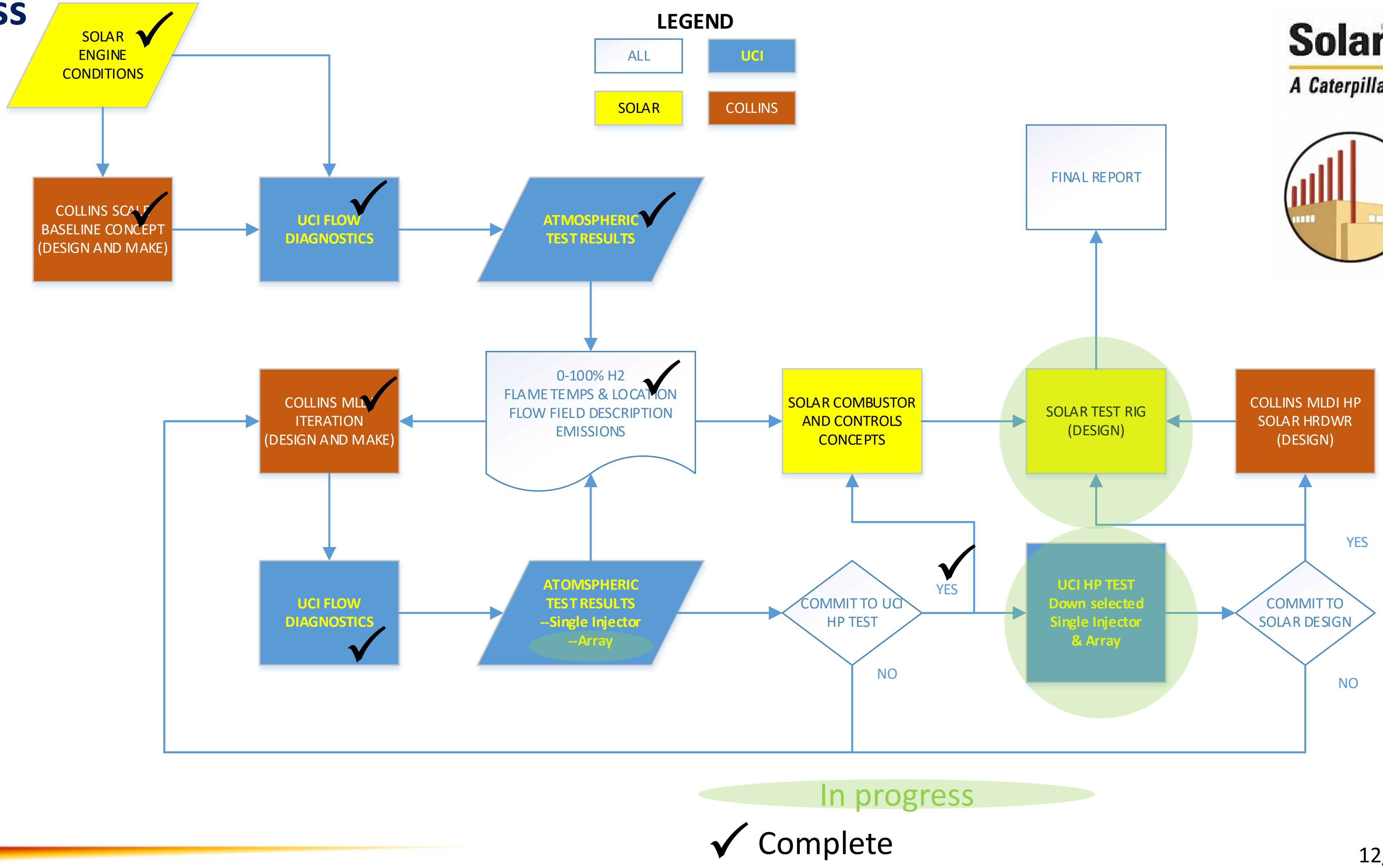
Cost Share: $200,000

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

Extension to March 9 2025 executed

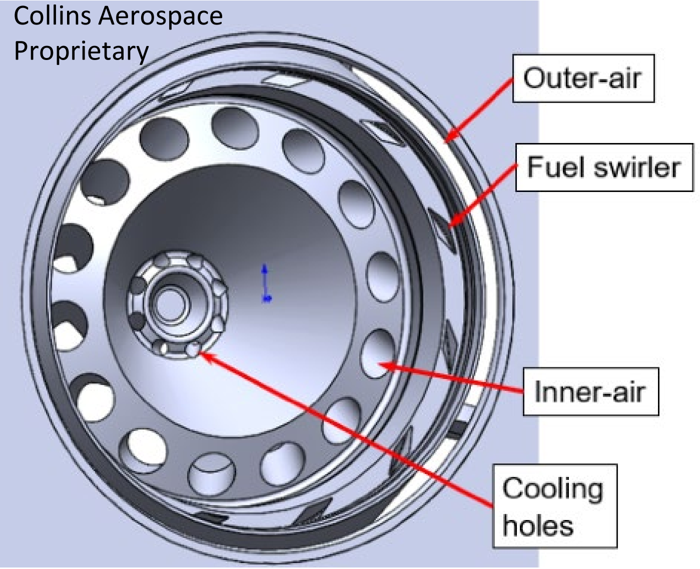
Workflow and Team

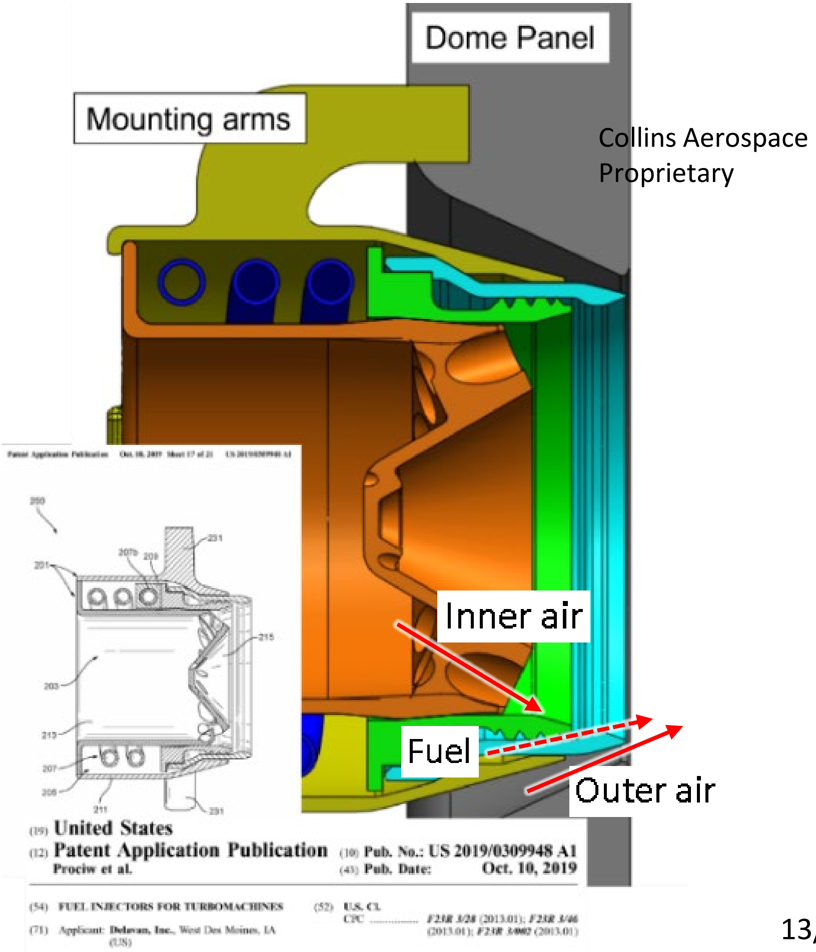
- **Progress**



Technical Approach – CFD and Manufacturing

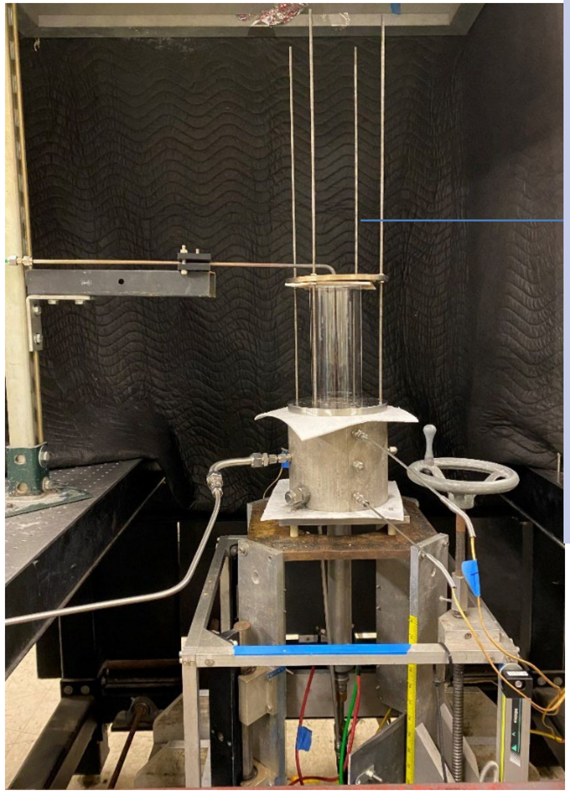
- Design of Experiments to establish the geometry variations
- Computational Fluid Dynamics to size air and fuel circuits
    - Effective area targets: 0.145in^2 air, 0.0055in^2 fuel → expected 5-15% decrease for rough surface finish
- Additive manufacturing: Inconel 625

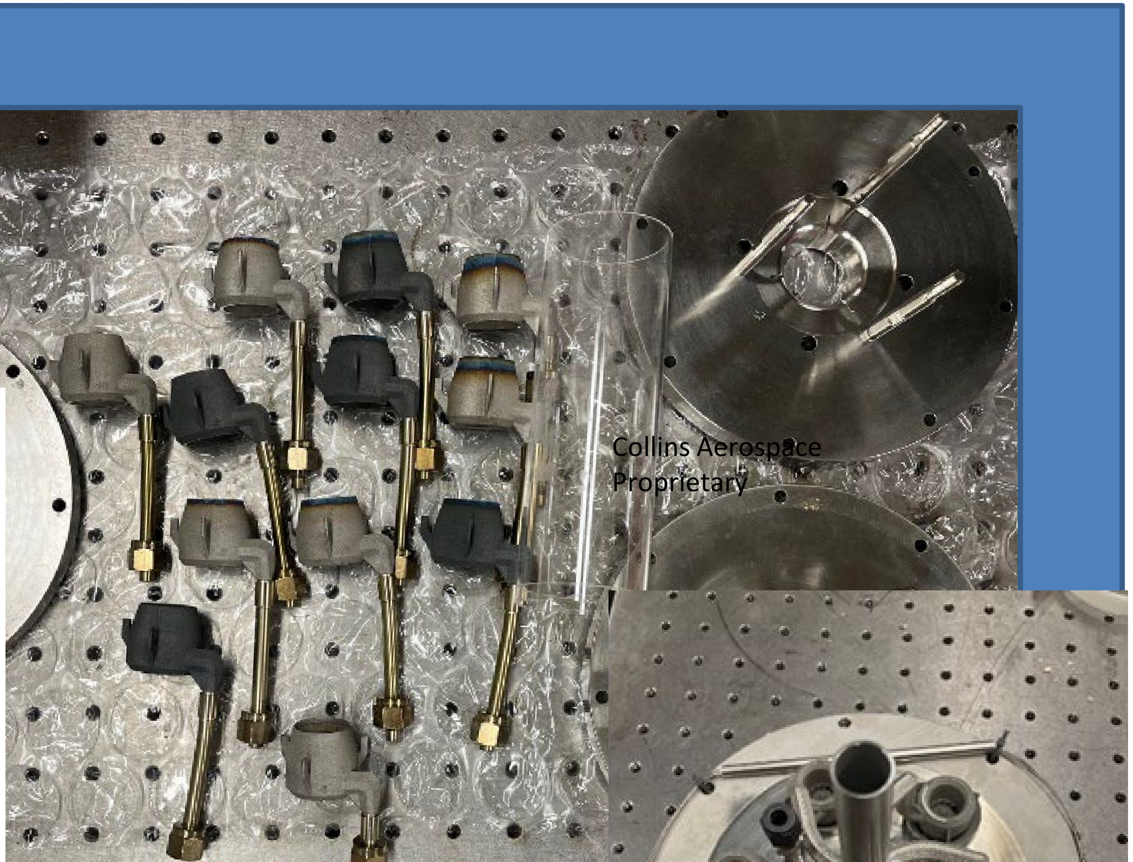


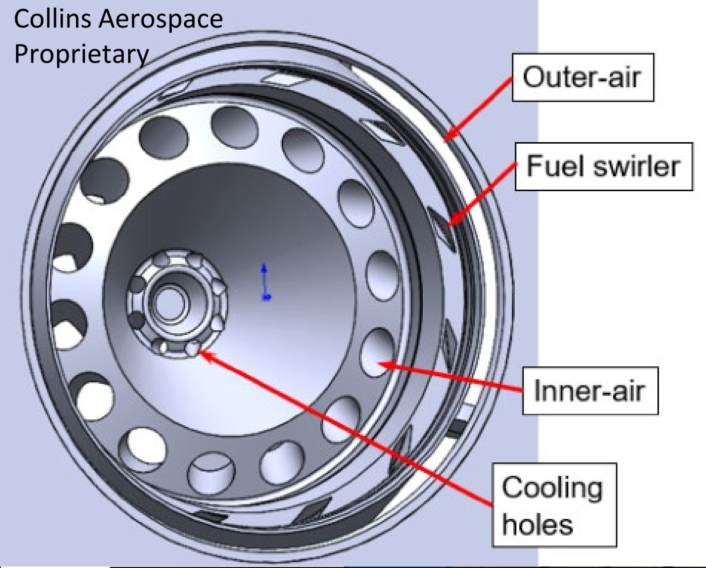


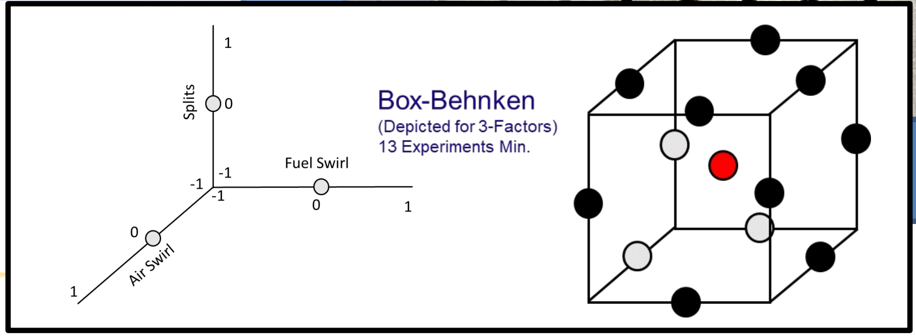
Injectors

- **Individuals**
  - 13 for pure B-B design
  - 3 for correlation validation
- **Downselect for Array**









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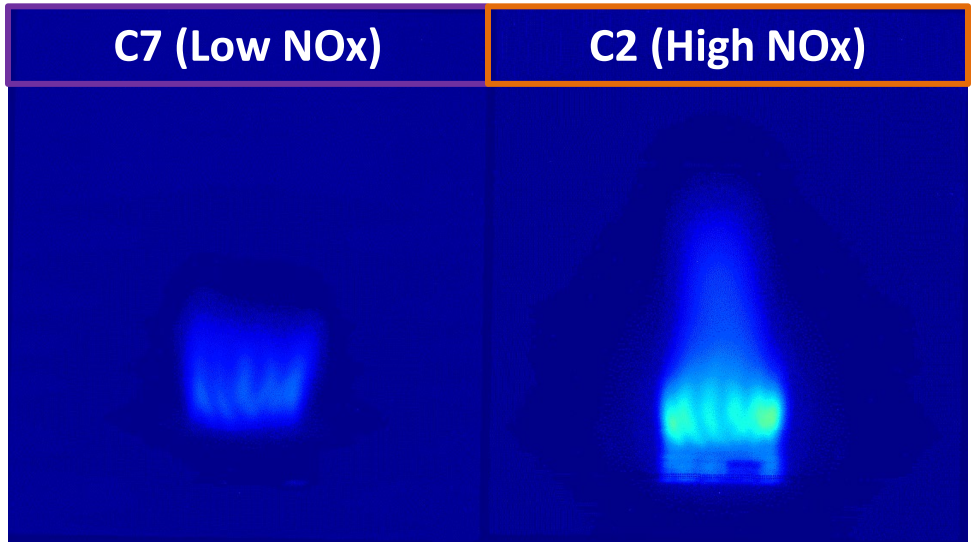
Previous Observations

- GT2023-101577 and GT2023-102632
- 770 test points obtained
- Successful adaptation of LDI injectors from liquid to H2 and H2/NG Blends
- Highly consistent effective areas
  - Additive manufacturing (surface roughness)
- Fuel flexible: 100% NG ↔ 100% H2

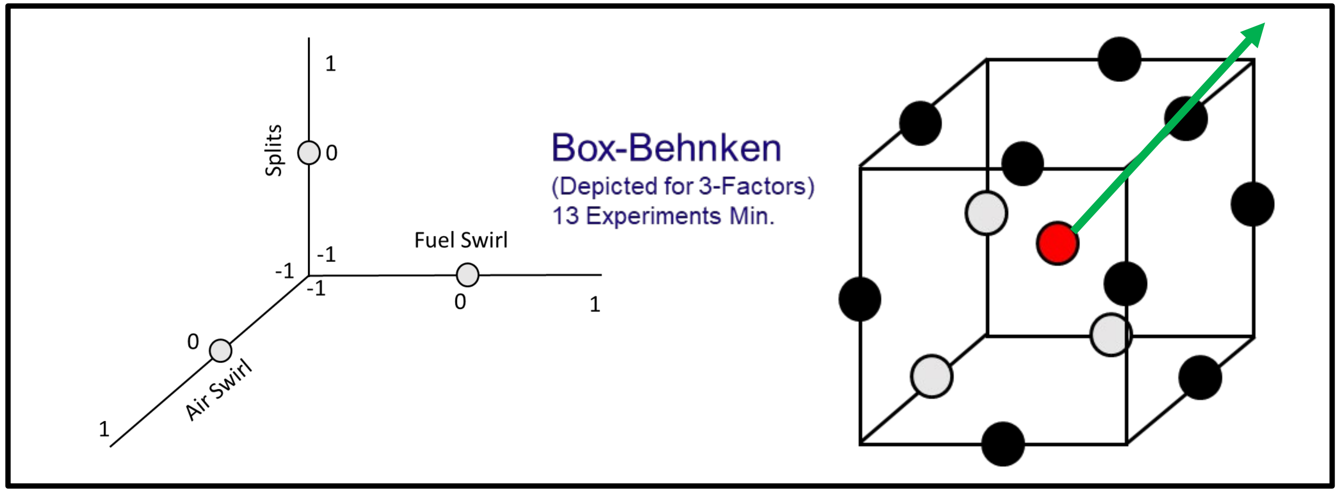
- Stability (↓ LBO) is enhanced by…
  - ↑ H2
  - ↓ air split
  - ↓ air swirl
- NOx is decreased with…
  - ↑ air split
  - ↑ air swirl
  - ↓ preheat/AFT
- Correlation between NOx and OH* average brightness



Config.	Air Split	Air Swirl Angle	Fuel Swirl Angle
2	-1	1	0
7	1	1	0

ANOVA Response Surface Indicated "Direction" for Improved Configuration

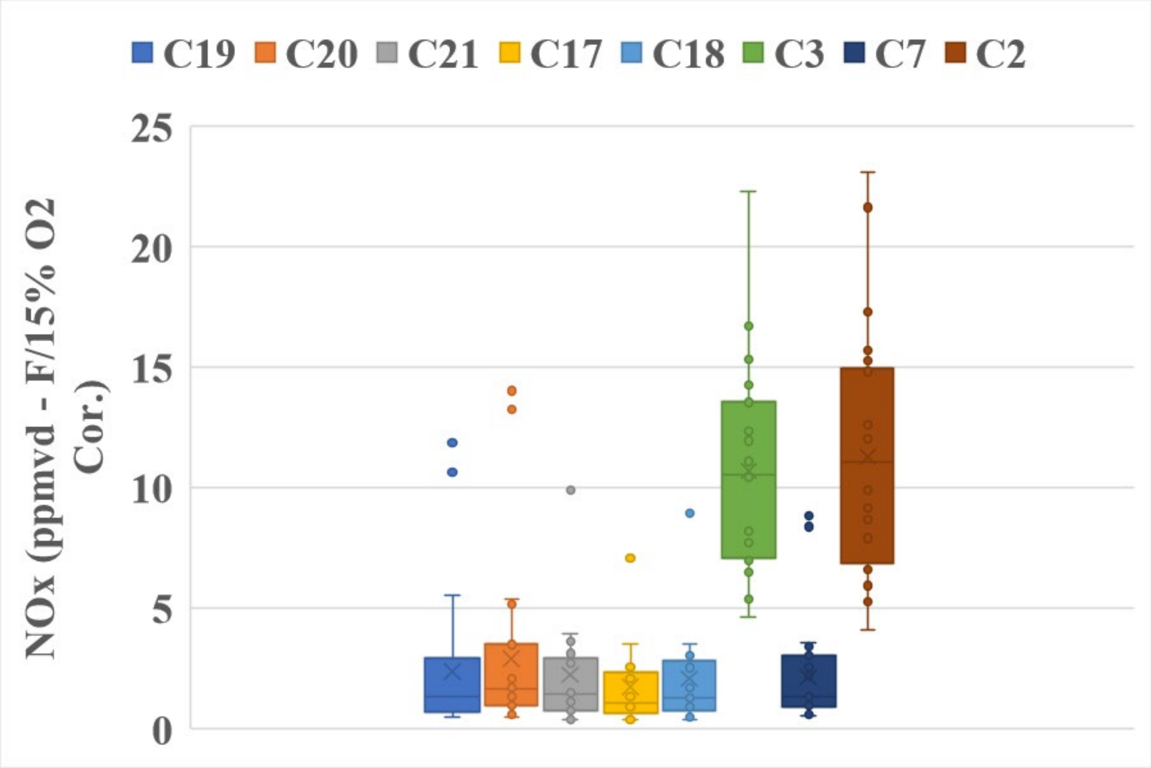
- **Further design refinement based on original ANOVA**
  - **Led to development and fabrication of configurations 17-21**
  - **New atmospheric tests carried out with new configurations**
    - ✓ **Effective area validation**
    - ✓ **Emissions performance (using same range of parameters as before)**
      - **preheat temperatures,**
      - **%hydrogen,**
      - **% pressure drop,**
      - **AFTs**
    - ✓ **Repeated some configurations to confirm prior results (9 months prior)**



Atmospheric Effective Areas and Emissions

- **Effective Areas and Emissions of repeated nozzles match previous studies**
- **C17 did achieve improved NOx performance as predicted**

Injector Configuration	Avg. NOx (ppmvd-FO15)
2 (INJ 2, Plate 3)	11.26*
3 (INJ 3, Plate 2)	10.68
7 (INJ 7, Plate 1)	2.13
17 (INJ 17, Plate 1)	1.72
18 (INJ 18, Plate 1)	2.07
19 (INJ 18, Plate 3)	2.37
20 (INJ 19, Plate 3)	2.90
21 (INJ 20, Plate 3)	2.22



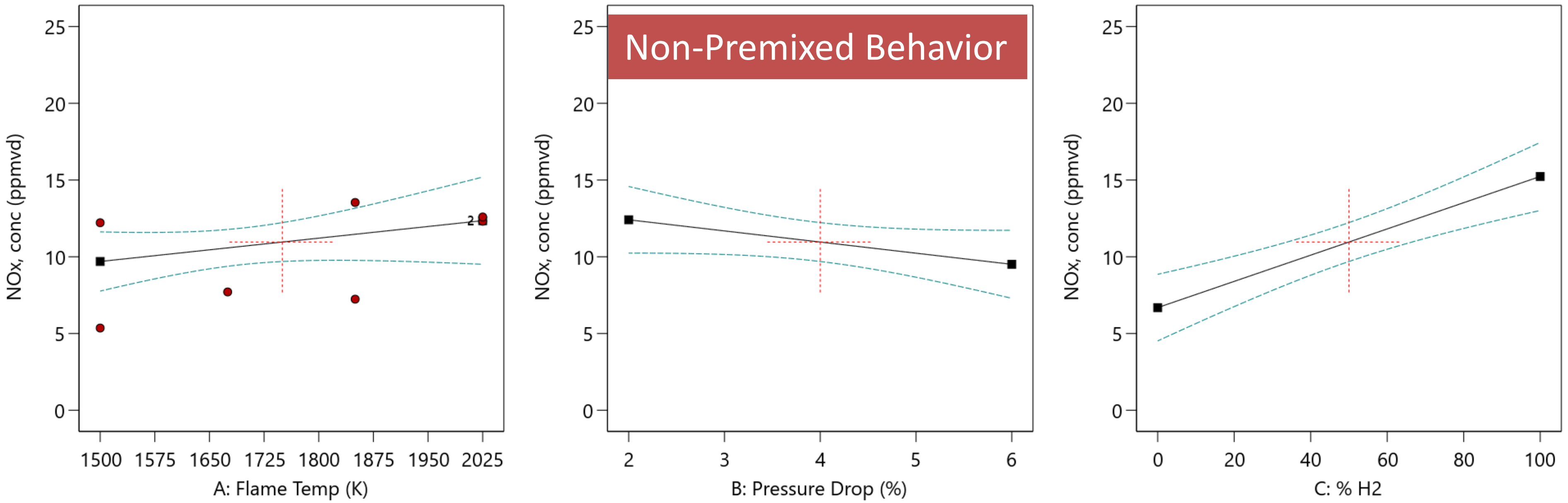
Atmospheric Emissions - NOx Model Comparison

- **C3 Model**

$$[NO_x] = 0.723703 + 0.005066 * A - 725268 * B + 0.085448 * C$$

  - **Minimal correlation to AFT**
  - **Strong linear dependence on fuel type**
  - **Inverse linear correlation to pressure drop**

Parameter	F-Value	P -Value
A – AFT (K)	1.80	0.1926
B – % PD	2.81	0.1071
C - % H2	24.40	<0.0001



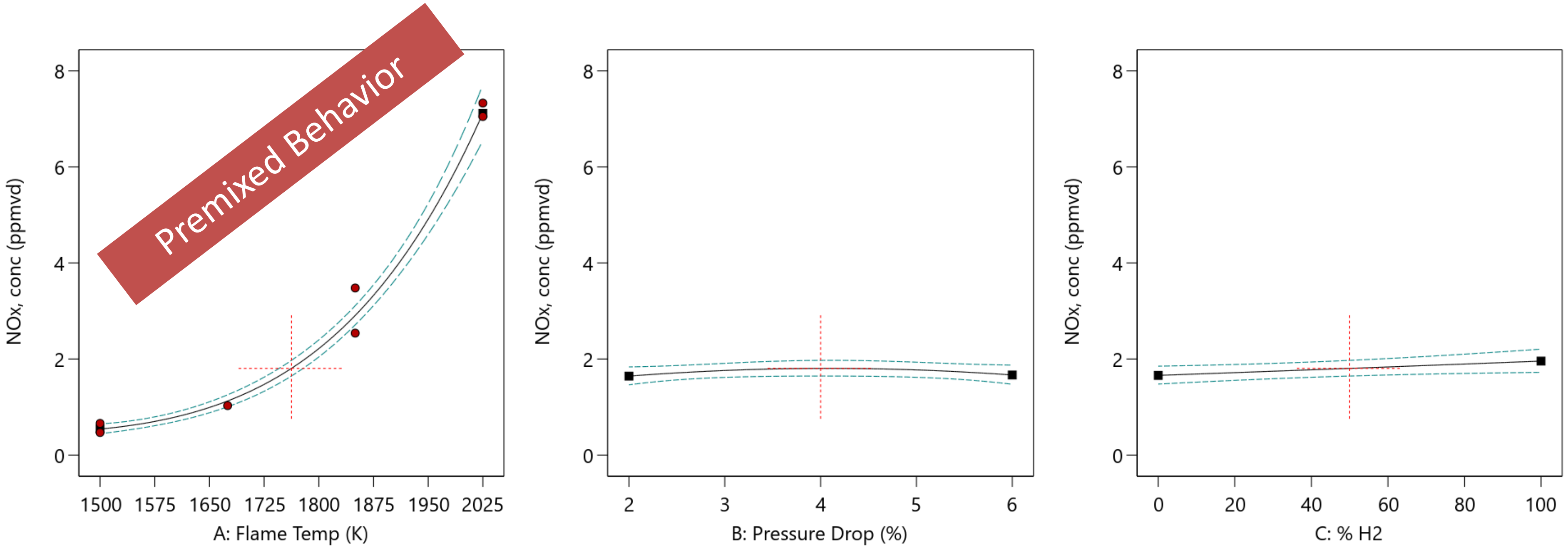
Atmospheric Emissions - NOx Model Comparison

- **C17 Model**

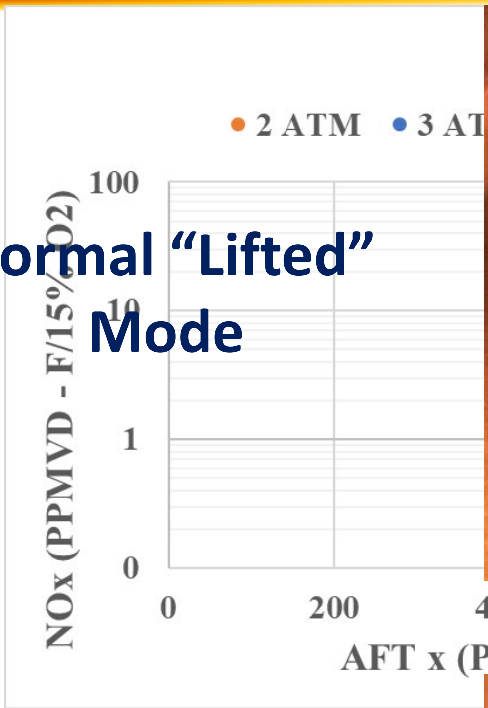
$$\sqrt{[NO_x]} = 10.70026 - 0.014636 * A + 0.116038 * + 0.001109 * C + 5.19701 * 10^{-6} * A^2 - 0.01421 * B^2$$

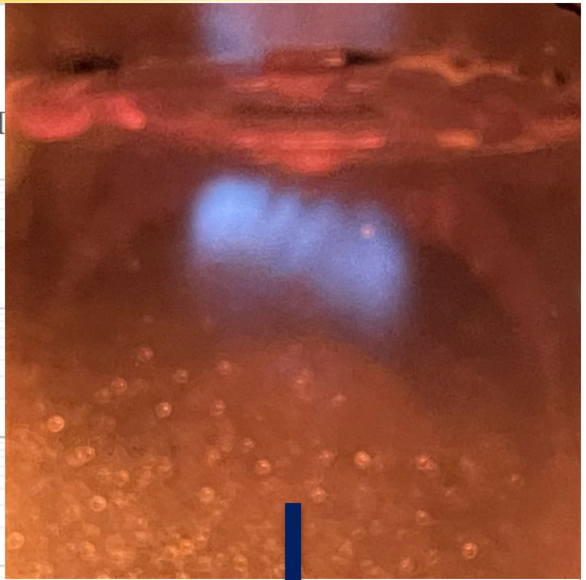
  - No Dependence on pressure drop or fuel type
  - Exponential relationship with AFT

Parameter	F-Value	P -Value
A/A^2 – AFT (K)	1123.29 (1050.03/73.26)	A: <0.0001 A^2: <0.0001
B/B^2 – % PD	2.9389 (0.0389/2.90)	B: 0.8456 B^2: 0.1040
C – % H2	5	C: 0.0368

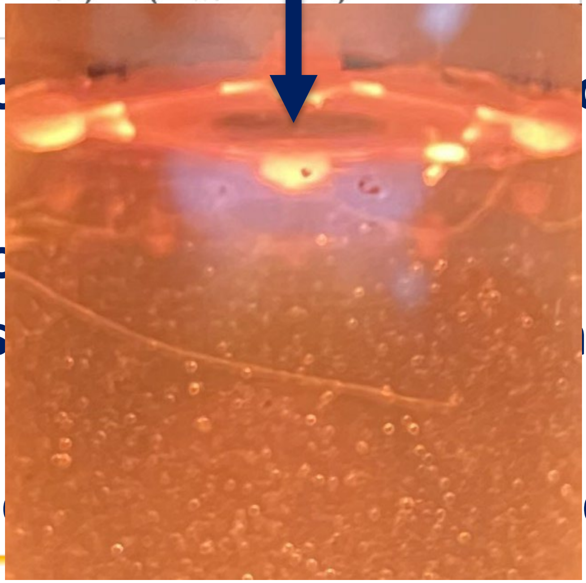


Elevated Pressure Testing





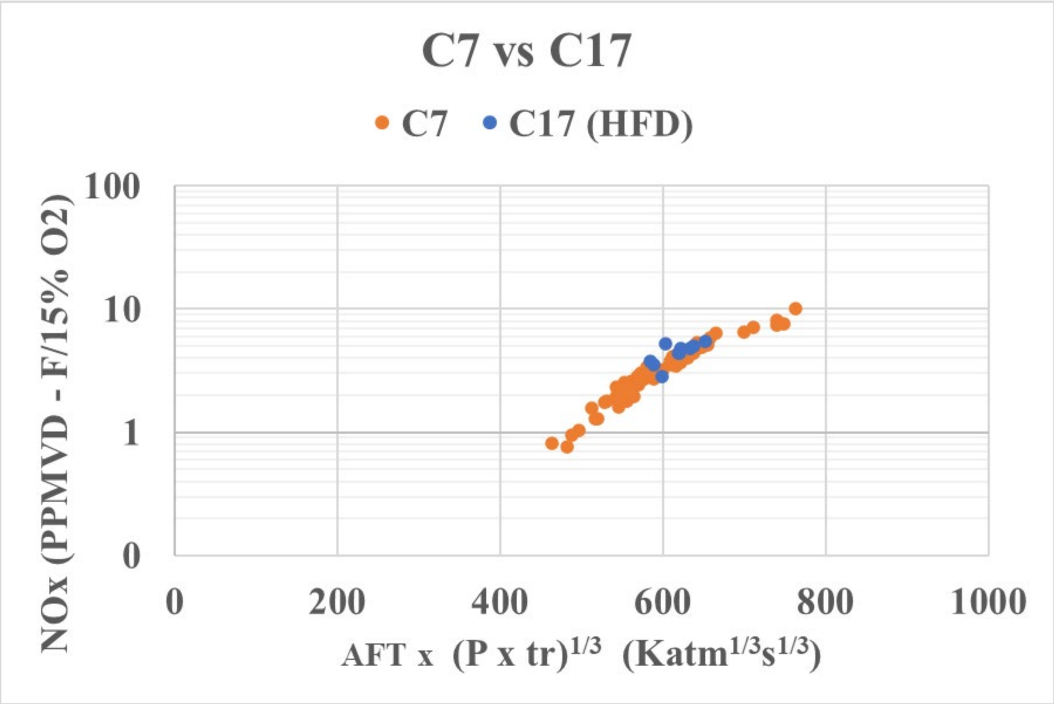
Normal "Lifted" Mode



HFD "Collapsed" Mode

- NOx does not follo… or wrt AFT
- NOx linear wrt pr… transformed press… e (Oh transform)
- Oh Transform indi… d

- NOx does follow logarithmic behavior wrt AFT @ 2-3 atm
- High Frequency Dynamics observed at 4-6 atm, non-logarithmic behavior
- HFD causes premixed → non-premixed

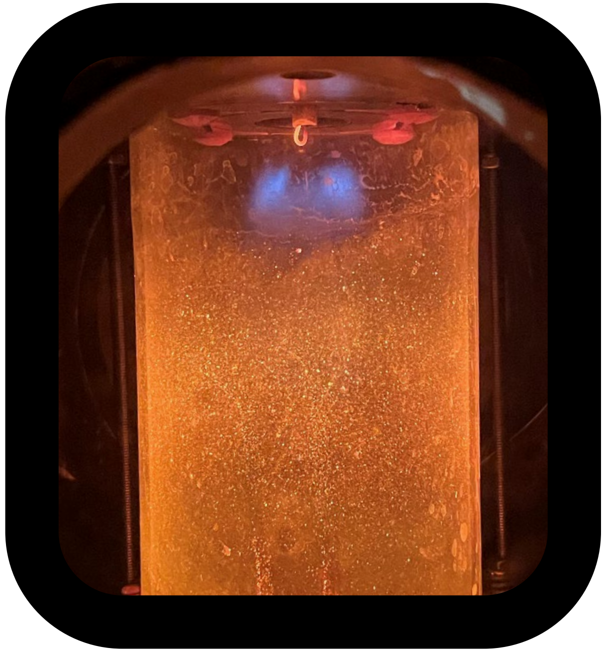


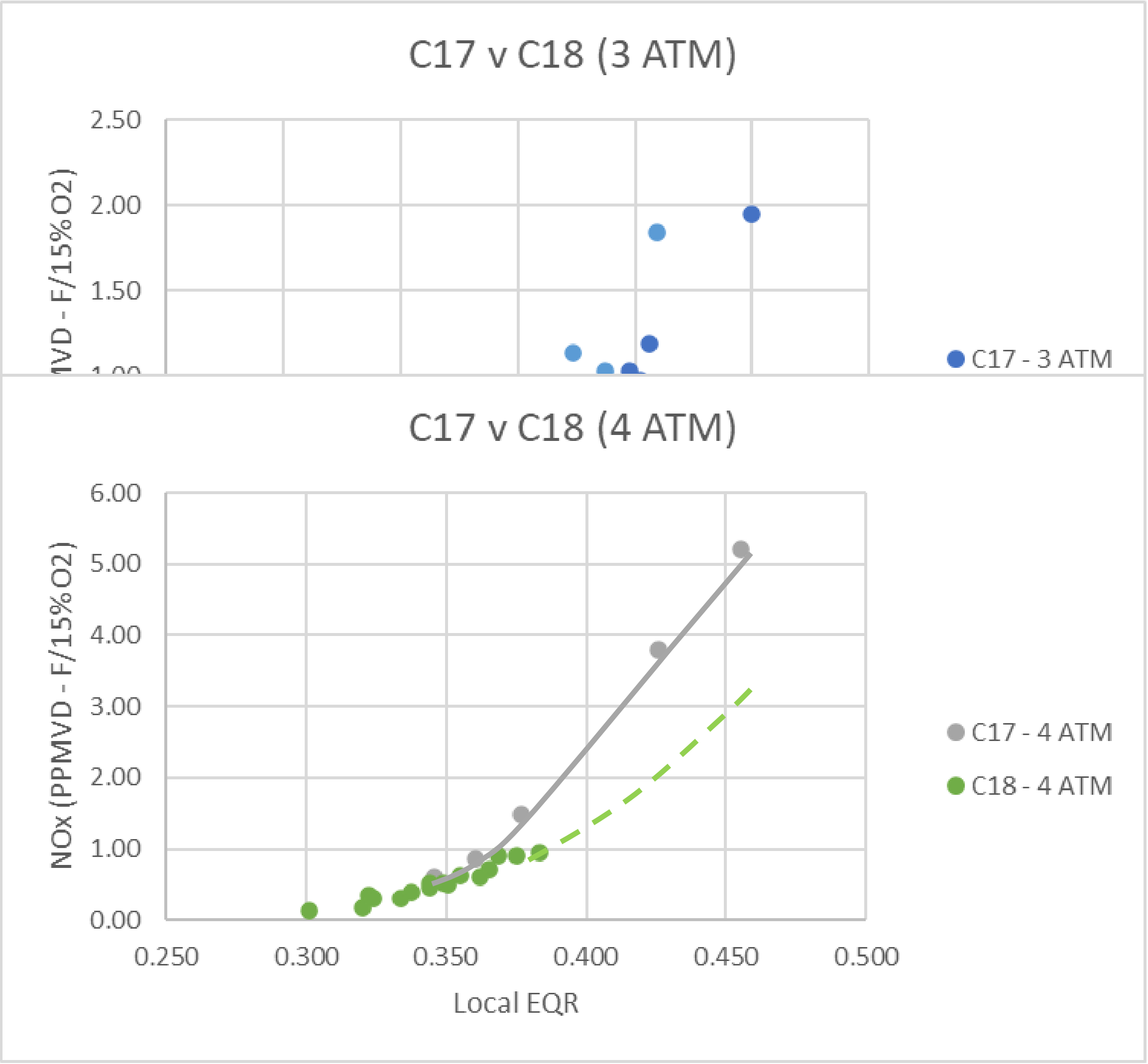
Elevated Pressure Testing

- **Shifted to Configuration 18**
  - **Modestly higher NOx (2.07) compared to Configuration 17 (1.72)**
  - **Design should “push” the reaction farther from injector face**
    - ✓ ~20% larger effective area

Configuration 18 results

- **Larger effective area limits fuel flow**
  - **New H_2 flow meter now in house and testing to 7-8 atm underway**
  - **Consistent lifted reaction**
    - ✓ **Facilitates more premixing**

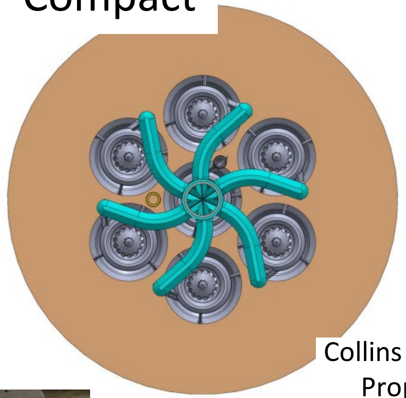




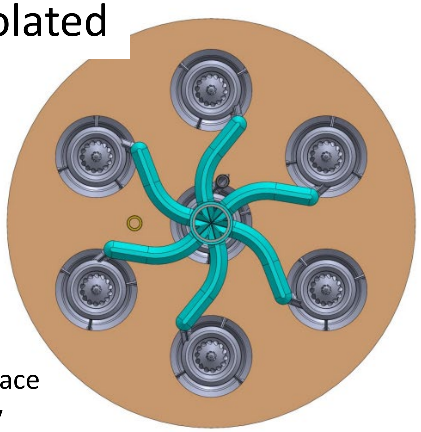
Array Testing

- **Configuration 7 used for initial array configuration**
  - **Low NOx with robust operability (consistent flame mode)**
  - **Arrays with two injector spacings developed**

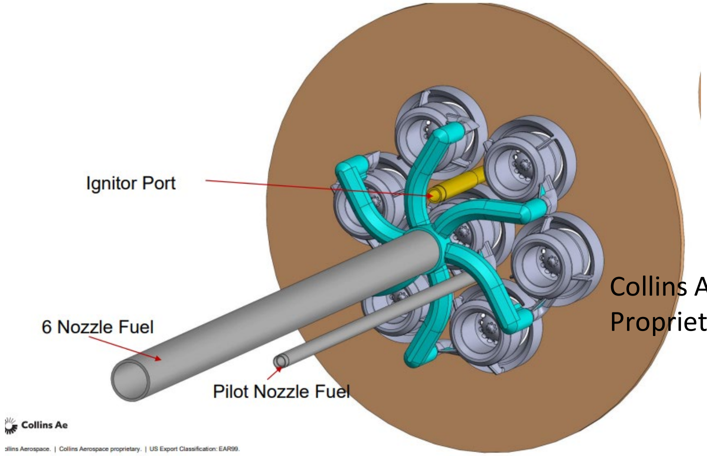
Compact



Isolated



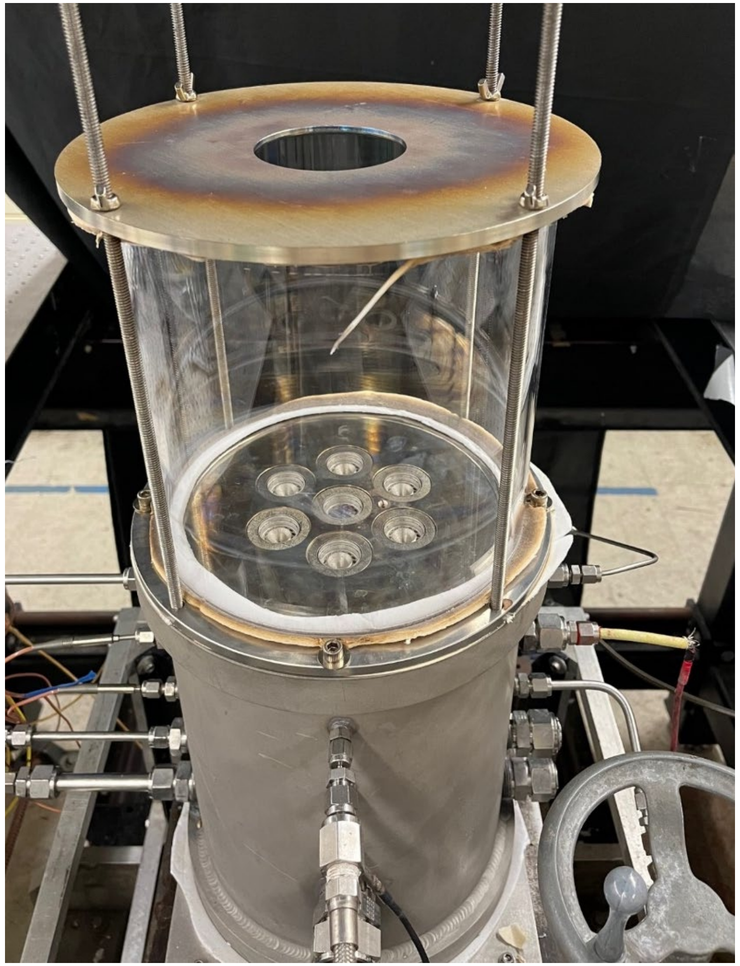
Collins Aerospace Proprietary

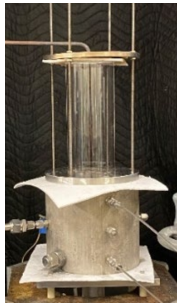


Array Testing

- **Updated airbox**

- **Array C7 – Version 1**





Effective Area

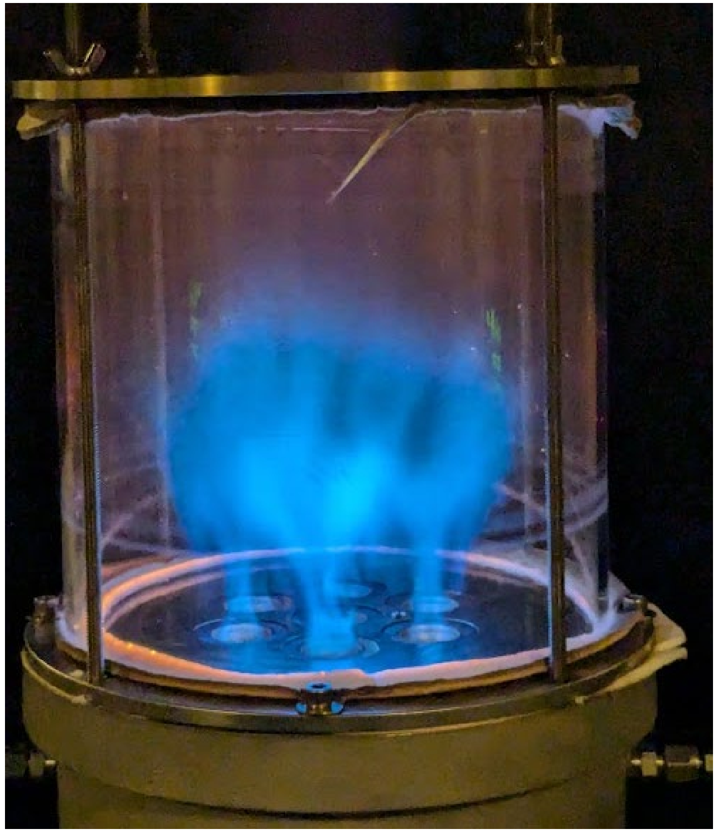
- **Compact C-7 array**
  - **Single C7 Injector: 0.154 sq inches**
  - **x 7 = 1.078 sq inches**
- **Results are as expected (single and array effective areas are within 3%)**

% Pressure Drop	Flowrate (SCFM)	DP (inH2O)	Discharge Pressure (PSIG)	Exit Pressure (PSIA)	Mass Flow (lb/s)	T (F)	EA (in^2)	P1/10	P1-P2	Valid?
2.01%	87.844	8.368	14.998	14.696	0.110	70	1.084	40.719	8.368	Y
2.22%	92.361	9.227	15.029	14.696	0.116	70	1.085	40.719	9.227	Y
2.68%	102.327	11.222	15.101	14.696	0.128	70	1.087	40.719	11.222	Y
2.93%	106.549	12.274	15.139	14.696	0.134	70	1.081	40.719	12.274	Y
3.40%	115.502	14.325	15.213	14.696	0.145	70	1.082	40.719	14.325	Y
4.47%	131.604	19.063	15.384	14.696	0.165	70	1.063	40.719	19.063	Y
1.59%	75.809	6.567	14.933	14.696	0.095	70	1.059	40.719	6.567	Y
2.44%	95.418	10.196	15.064	14.696	0.120	70	1.065	40.719	10.196	Y
3.80%	120.648	16.098	15.277	14.696	0.151	70	1.064	40.719	16.098	Y
5.00%	139.838	21.418	15.469	14.696	0.175	70	1.063	40.719	21.418	Y

Initial Array Tests

- **Images and videos (natural gas)**

Center Injector
400 F preheat
ϕ = 0.98
$\Delta P/P$ = 3%



All Injectors
400 F preheat
ϕ = 0.81
$\Delta P/P$ = 3%

Pilot LBO (Center Injector)

- **Array—Significantly reduced stability**

				Temperature							
	Air (PSI)	DP (PSIG)	Fuel %	Pilot (F)	Array (F)	Airbox (F)	Preheat (F)	PD (%)	Fuel (SCFM)	Air (SCFM)	LBO-phi
1	54	0.86	93	401	536	420.8	710	5%	1.46	99.6	1.02
2	41.47	0.52	67.5	428	473	377.6	600	4%	1.05	80.8	0.91
3	41.054	0.473	71.5	312.8	374	305.6	440	4%	1.11	80.2	0.97
4	32.54	0.382	53.5	392	460.4	366.8	600	3%	0.83	67.4	0.86
5	55.19	0.89	91	426.2	539.6	426.2	710	5%	1.42	101.3	0.98
6	41.12	0.53	67	397.4	298.4	383	600	4%	1.04	80.3	0.91
7	41.106	0.478	71.5	323.6	384.8	318.2	440	4%	1.11	80.3	0.97
8	32.029	0.376	51.5	401	464	370.4	600	3%	0.79	66.7	0.83

- **Single Injector (for reference) 0.44-0.54 LBO**
  - **80 mm quartz tube**

Run Order	Pressure Drop %	Preheat Temp [F]	Fuel Compoisition %H2	Fuel Composition %Methane	Blue PSI Reading - Expected	Blue PSI Reading - Measured	Channel Reading Methane %	Channel Reading H2 %	LBO - Minimum Equivalence ratio
1	6	710	0	100	66.880	61.400	53.70	0.00	0.5173156459
2	4	980	0	100	44.364	42.300	34.20	0.00	0.4376648101
3	4	440	0	100	61.036	53.400	50.50	0.00	0.5432630381
4	2	710	0	100	30.835	28.400	27.70	0.00	0.4671173236

Array Test Matrix

- Fix pressure loss and inlet air preheat
- Vary
  - Bulk AFT (overall phi)/firing temp
  - Pilot/Main split (local temps)
  - NG, 50/50, H2
  - Local overall AFT (phi)
- 36 points for <u>each array</u>
  - Will add some repeats

STD	Preheat (K)	PD %	% H2	Pilot Temp (K)	Main Temp (K)	Global Temp (K)
1	700	4	0	1500	1500	1500
2	700	4	0	1440	1510	1500
3	700	4	0	1560	1490	1500
4	700	4	0	1620	1480	1500
5	700	4	0	1700	1700	1700
6	700	4	0	1640	1710	1700
7	700	4	0	1760	1690	1700
8	700	4	0	1820	1680	1700
9	700	4	0	1900	1900	1900
10	700	4	0	1840	1910	1900
11	700	4	0	1960	1890	1900
12	700	4	0	2020	1880	1900
13	700	4	50	1500	1500	1500
14	700	4	50	1440	1510	1500
15	700	4	50	1560	1490	1500
16	700	4	50	1620	1480	1500
17	700	4	50	1700	1700	1700
18	700	4	50	1640	1710	1700
19	700	4	50	1760	1690	1700
20	700	4	50	1820	1680	1700
21	700	4	50	1900	1900	1900
22	700	4	50	1840	1910	1900
23	700	4	50	1960	1890	1900
24	700	4	50	2020	1880	1900
25	700	4	100	1500	1500	1500
26	700	4	100	1440	1510	1500
27	700	4	100	1560	1490	1500
28	700	4	100	1620	1480	1500
29	700	4	100	1700	1700	1700
30	700	4	100	1640	1710	1700
31	700	4	100	1760	1690	1700
32	700	4	100	1820	1680	1700
33	700	4	100	1900	1900	1900
34	700	4	100	1840	1910	1900
35	700	4	100	1960	1890	1900
36	700	4	100	2020	1880	1900

Outline

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

Next Steps

- Finish up Config 18 (and 17) high pressure single injector testing
- Array testing (Config 7)
  - 36 point matrix: close coupled spacing
  - 36 point matrix: isolated spacing
    - ✓ Emissions
    - ✓ OH* chemiluminescence: 3D flame tomography
- Finalize design for Solar Turbines test rig
- Final Reporting

Acknowledgments

- **Collins Aerospace**
  - Ottavio DeBeni
  - Phil Buelow
  - Jason Ryon
  - Brandon Williams

- **Solar Turbines**
  - Mike Ramotowski
  - Raj Patel
  - Jon Duckers

- **US Department of Energy**
  - Matt Adams, Katelyn Ballard, John Crane

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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)

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Predictive Modeling of NO Emissions from Lean Direct Injection of Hydrogen and Hydrogen/Natural Gas Blends using Flame Imaging and Machine Learning (2024). **Int'l J. Turbomachinery Propulsion and Power** (I. Escudero, V. McDonell), in press

Two conference papers (Combustion Institute US National meeting)

Two MS theses (third in progress)

One UTSR fellow (M. Overbaugh)

Additional papers planned