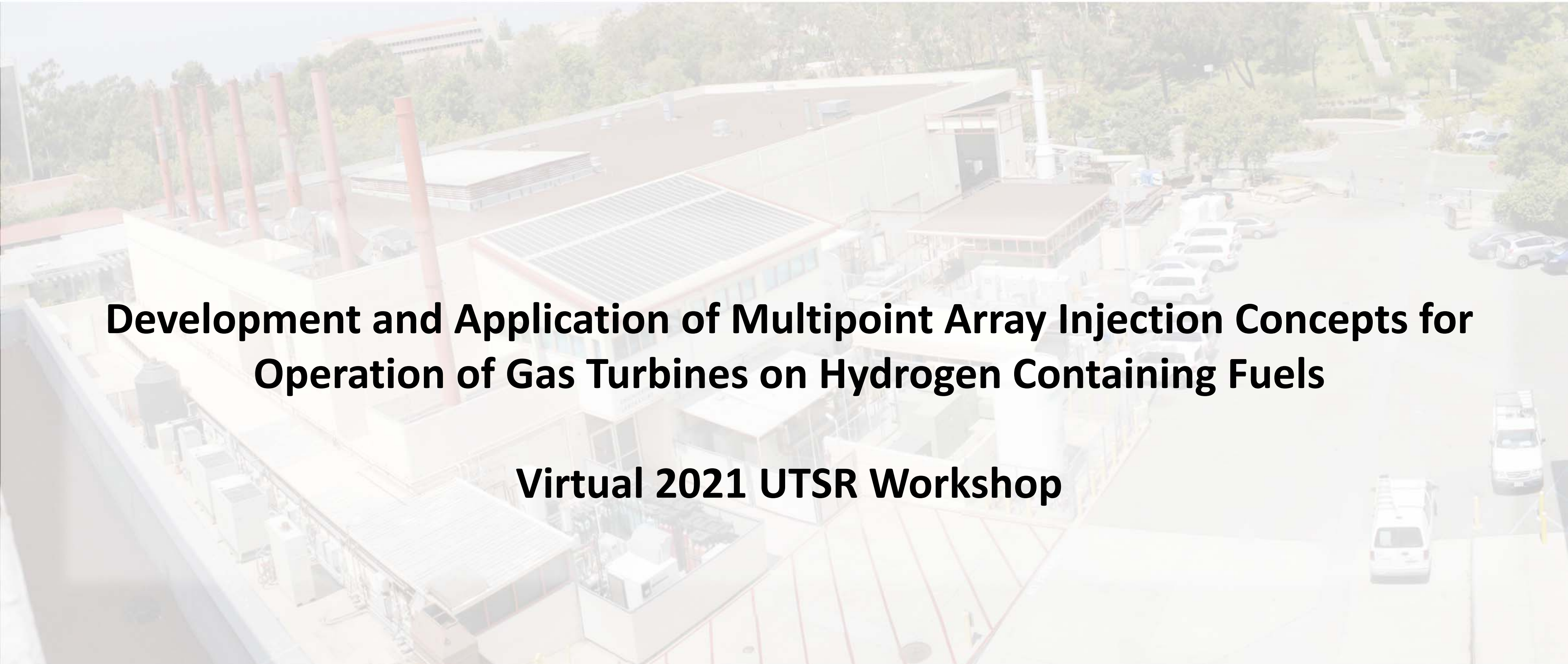


Development and Application of Multipoint Array Injection Concepts for Operation of Gas Turbines on Hydrogen Containing Fuels

Virtual 2021 UTSR Workshop

UCI Combustion Laboratory
UCIrvine University of California

Solar Turbines
A Caterpillar Company

Collins Aerospace

Vincent McDonell
8 November 2021
mcdonell@UCICL.uci.edu

Outline

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

Background

- **UCI Combustion Laboratory**
  - **Founded in 1970**
    - ✓ **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

Air compressors
Fuel mixing station
Test cells
DG test area
Fuel compressors
Liquid fuel storage/pumps
DG test area

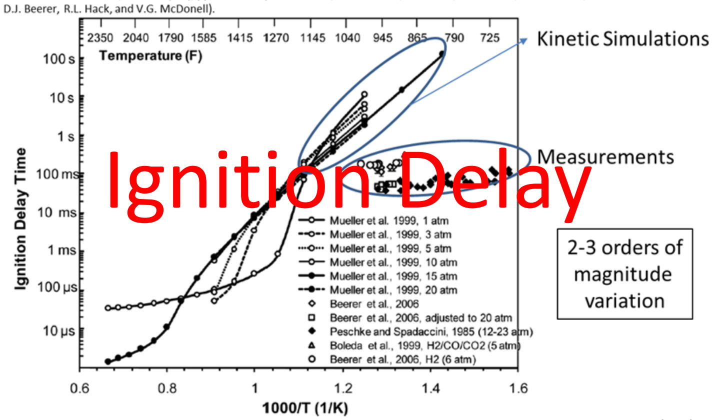
Perspective—High Hydrogen

Time	Project/Research Study Title	Scope
1997	Stand Alone Power Plant Running on Biomass Gas (EPRI)	Ignition delay times for lean H2/CO/Air mixtures
2001-2005	Fuel Flexible Combustor for MTG (CEC)	Retrofit Capstone gas turbine engine for operation on 100% H2
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	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 (Captone/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

20+ years of research

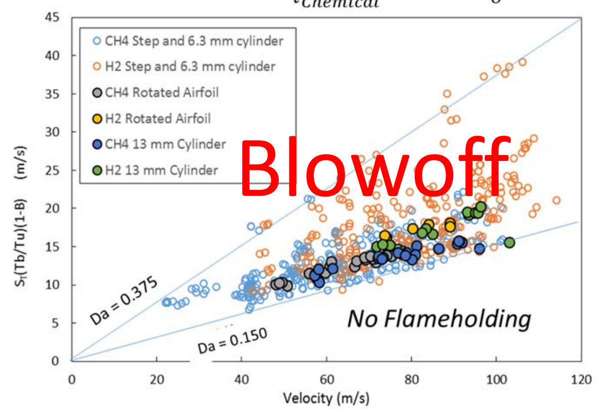
Gas Turbine Emphasis

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).



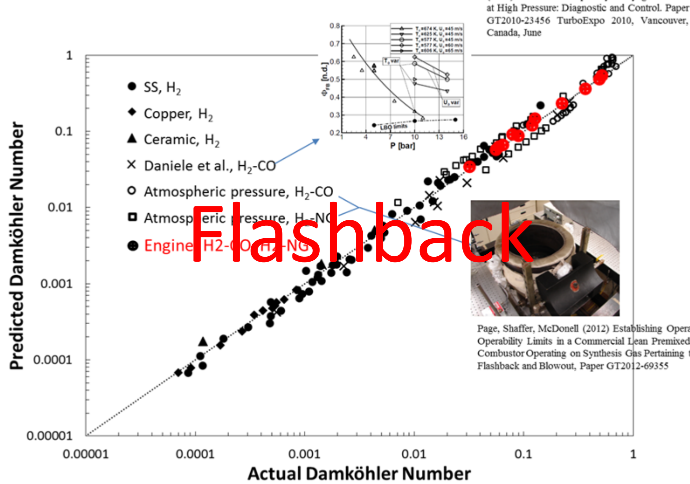
AUTOIGNITION OF HYDROGEN AND AIR IN A CONTINUOUS FLOW REACTOR WITH APPLICATION TO LEAN PREMIXED COMBUSTION (2008). *ASME J. Engr. Gas Turbines and Power*, Vol 130, 051507-1 to 051507-9, September (D.J. Beerer and V.G. McDonell).

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

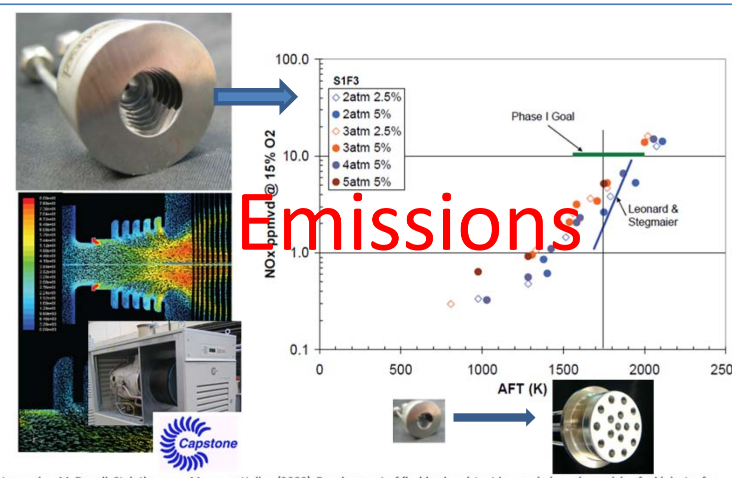


PREDICTING FLAMEHOLDING FOR HYDROGEN AND NATURAL GAS FLAMES AT GAS TURBINE PREMIXER CONDITIONS (2016). *ASME J. Engr Gas Turbines and Power*, Vol. 138(12), pp 121502-1 - 121502-9 (E. Sullivan-Lewis and V.G. McDonell).

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



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

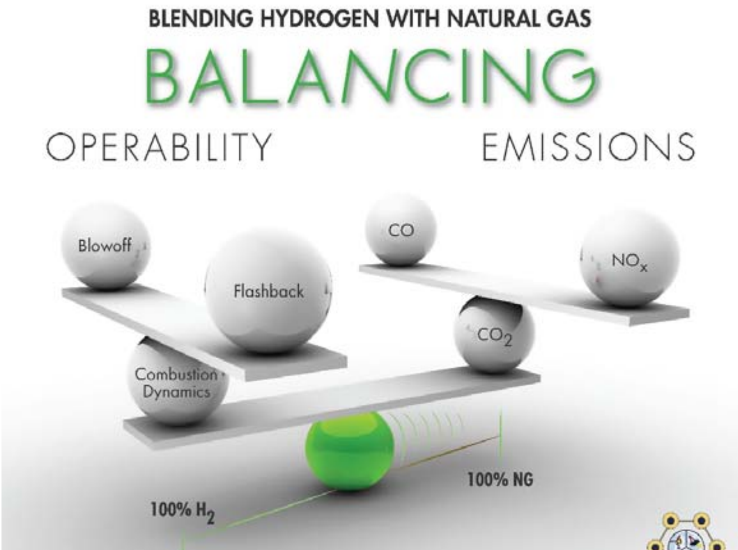


*Lee, Hernandez, McDonell, Steinthorsson, Mansour, Hollon (2009). Development of flashback resistant low-emission micro-mixing fuel injector for 100% hydrogen and SYNGAS fuels, Paper GT2009-59502, TurboExpo 2009.

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).

Perspective on Hydrogen or Hydrogen Addition to NG for GTEs

- **Interchangeability?**
- **What about combustion related considerations?**
  - **Operability**
    - ✓ **Wide flammability limits→ improved static stability limits**
    - ✓ **Autoignition?**
    - ✓ **Flashback?**
  - **Emissions**
    - ✓ **NOx Emissions (CO and CO2 inherently eliminated)**

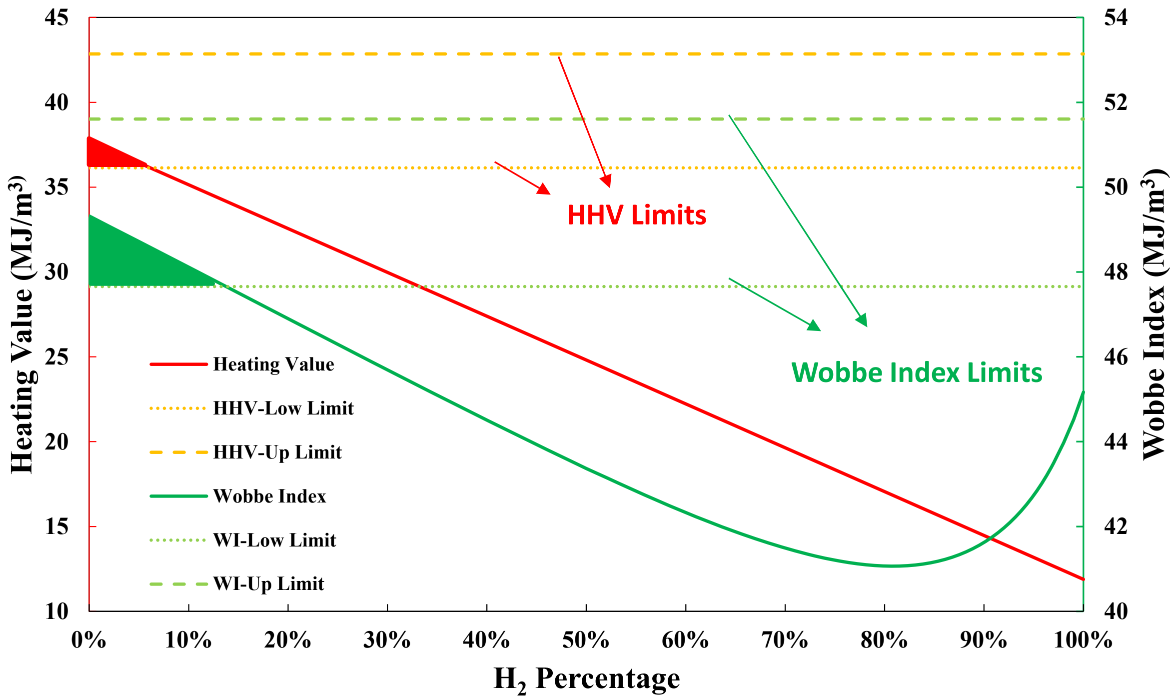


Advanced Power and Energy Program

Technical Questions

- **Interchangeability**
  - **Context of SCG Rule 30**

Hydrogen is relatively interchangeable with existing pipeline gas on energy throughput basis, yet 3x volume flow



Heating Value Limit: 6.1% addition
Wobbe Index Limit: 13.8% addition

$$Wobbe\ Index = \frac{HHV}{\sqrt{Sg}}$$

Technical Questions

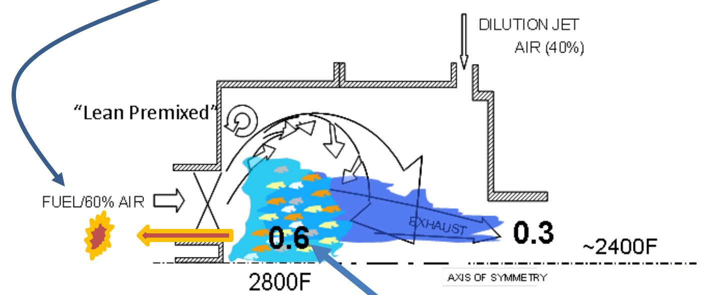
- Interchangeability?

- **What about combustion related considerations?**

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

  - **Emissions**
    - ✓ **NOx Emissions (CO and CO_2 inherently reduced as H_2 displaces fossil Carbon)**

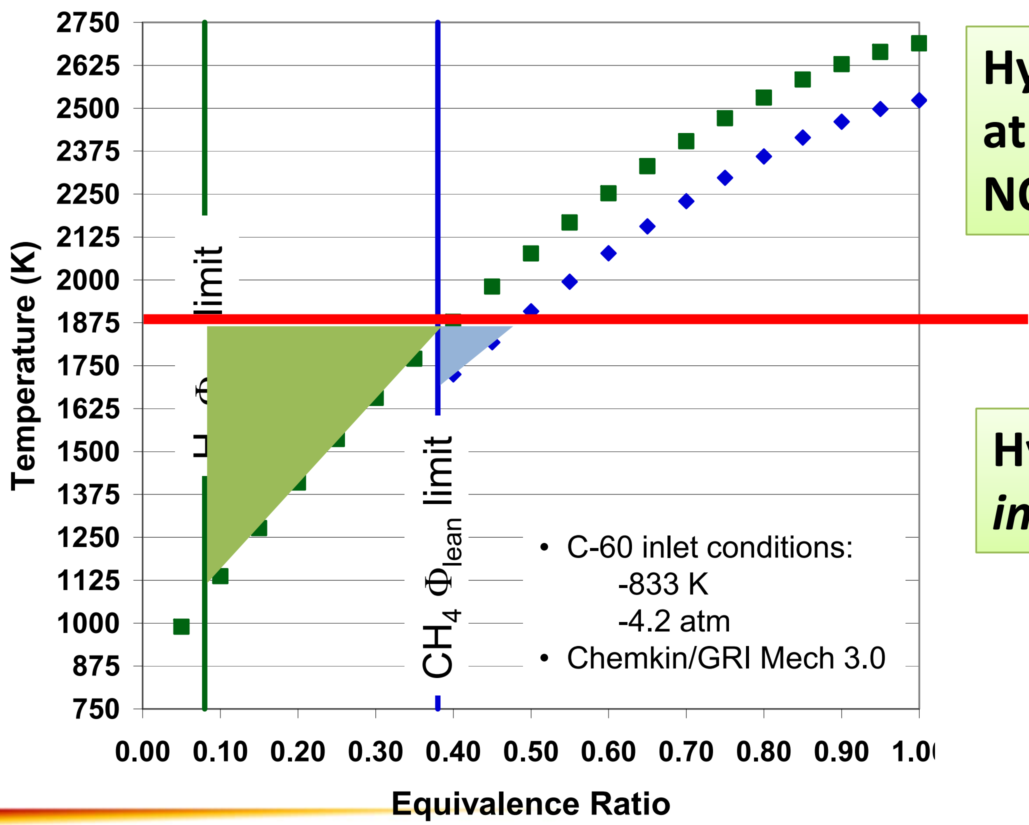
Flammable Mixture
Pressure up to 50 atm
Temperature up to 1200 F



0.5, 0.4?
2500, 2600 F?

Static Stability Limits

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



NOx trigger temperature

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

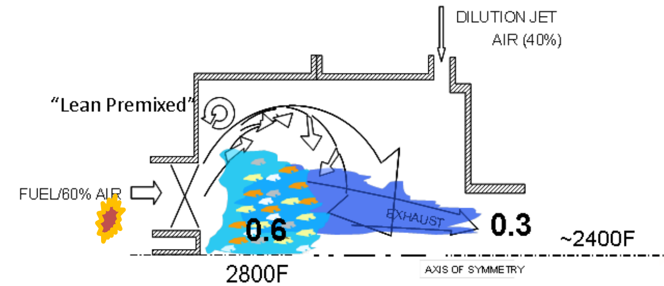
Hydrogen results in synergy between *improved stability* and *lower emissions*

Ignition Delay

- **Engine Implications**

Engine	Pressure (atm)	Air Temp (K)	Estimated Ignition Delay Time, msec H2/CO Based on Experiments	Estimated Ignition Delay Time, msec H2/CO CHEMKIN (Mueller)
GE 9H *	23	705	85	11800
Solar Taurus 65	15	670	153	-
Solar Taurus 60	12.3	644	221	-
Solar Mercury 50**	9.9	880	59	4941
GE LM6000 *	35	798	35	34850
Siemens V-94.3A *	17.7	665	141	-
Siemens V-94.2 *	12	600	336	-
Capstone C60**	4.2	833	140	1869

* Inlet temp estimated from ideal gas, isentropic compression
** Recuperated Engine
- represents no ignition within 1 min.

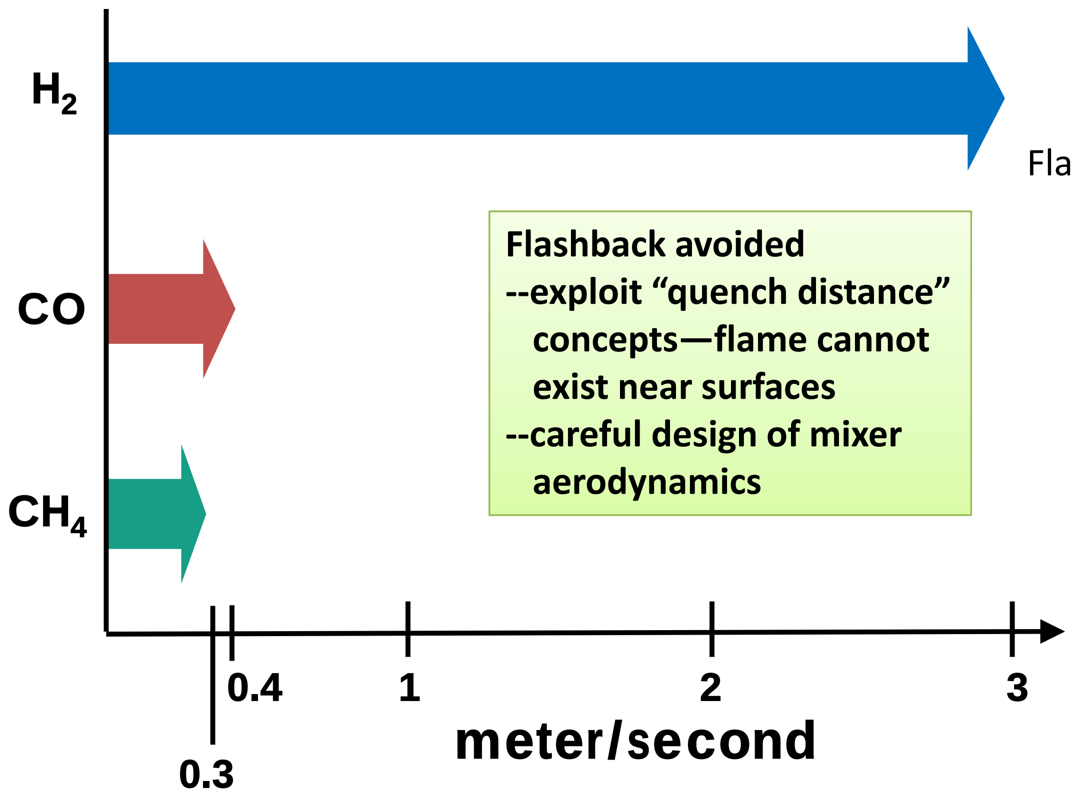


7x minimum safety factor

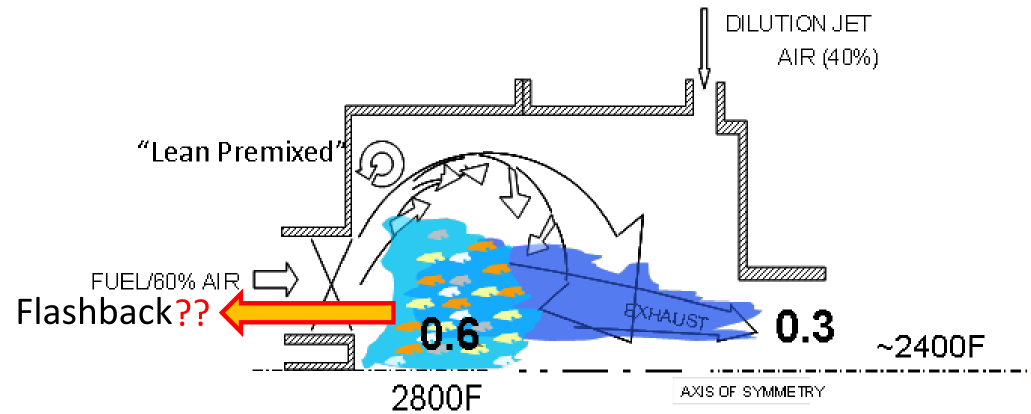
Autoignition *not an issue* with well designed premixer: all OEMs have shown or are in process of showing this

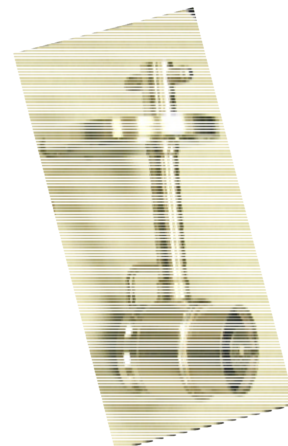
Flashback

- **Laminar Flame Speed (maximum value)**
  - **H2/air burns 10x faster than natural gas/air**



Flashback avoided
--exploit "quench distance" concepts—flame cannot exist near surfaces
--careful design of mixer aerodynamics





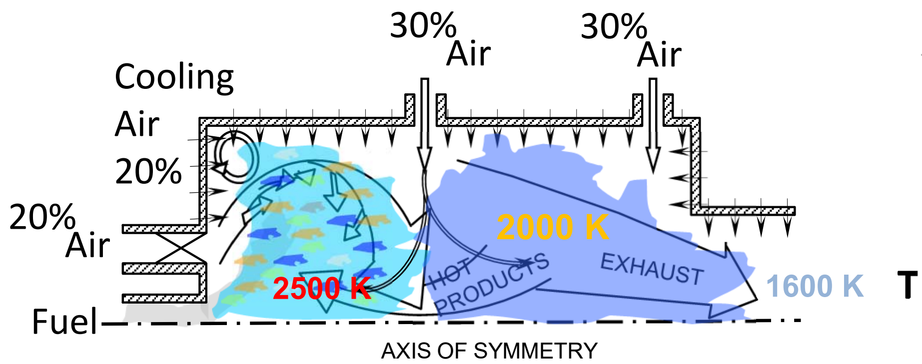
Single Large Injector

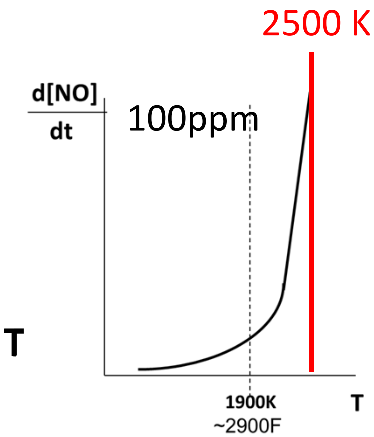
Many small injectors

Natural Gas Combustor NOx Emissions

- **Legacy**

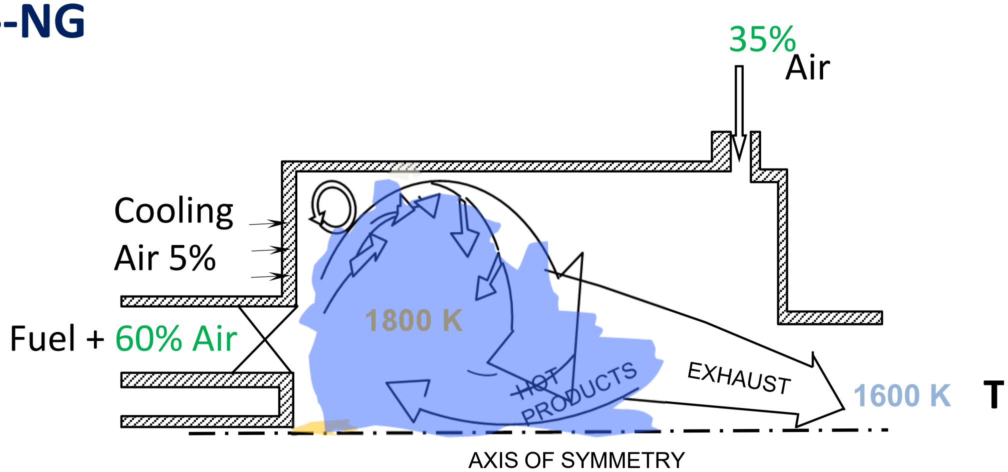
Fuel + Air
Massflow = 30 lb/s

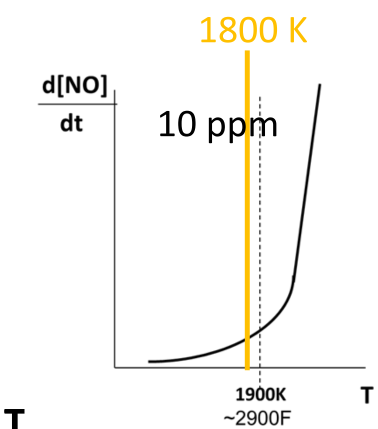




- **Lean Premixed--NG**

Fuel + Air
Massflow = 30 lb/s

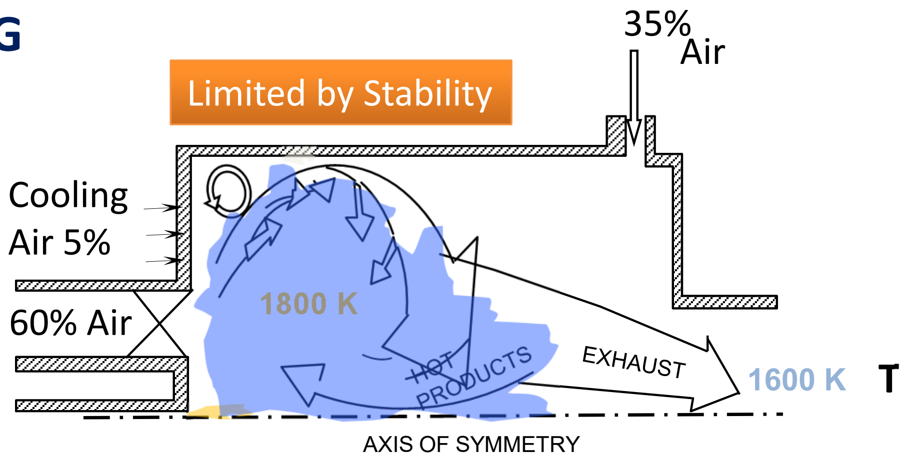


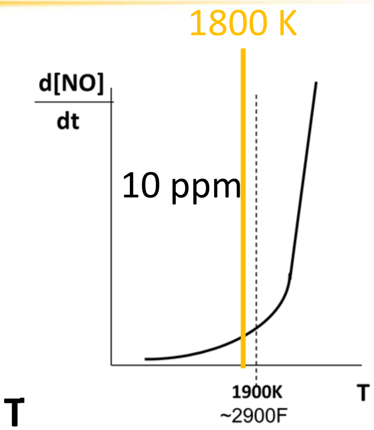


Natural Gas Combustor NOx Emissions w/Hydrogen

- **Lean Premixed NG**

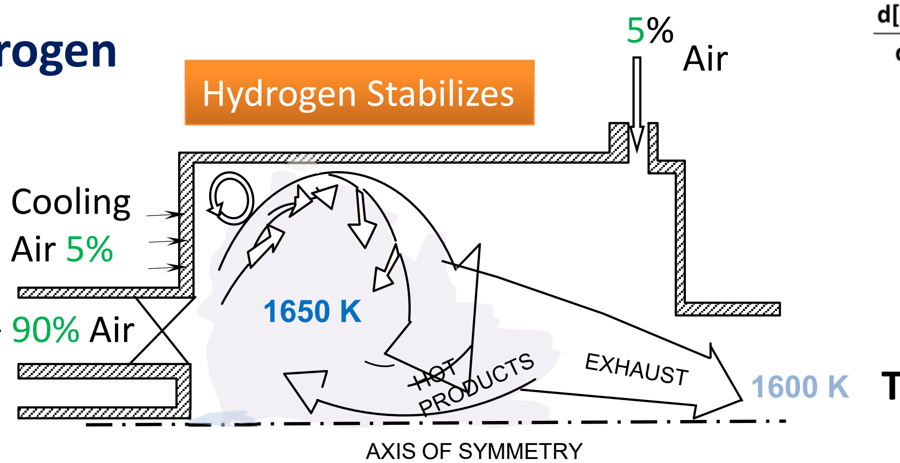
Fuel + Air
Massflow = 30 lb/s

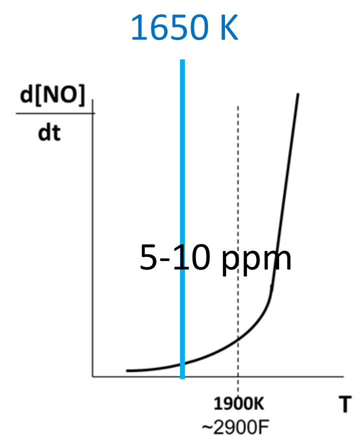




- **Lean Premixed Hydrogen**

Fuel + Air
Massflow = 30 lb/s

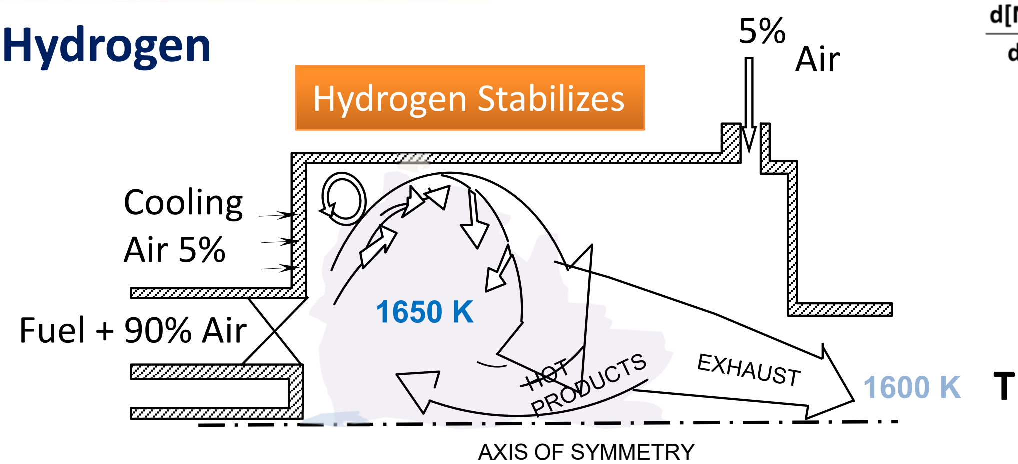


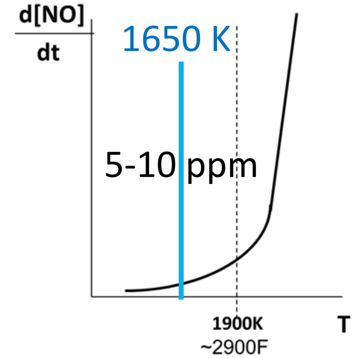


Natural Gas Combustor NOx Emissions w/Hydrogen

- **Lean Premixed Hydrogen**

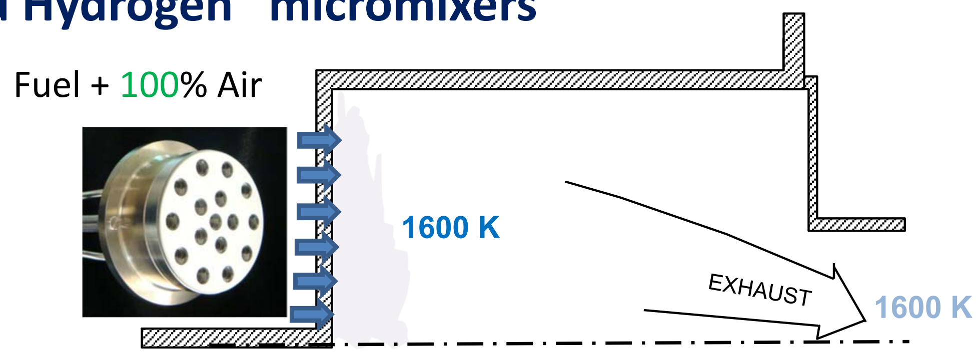
Fuel + Air
Massflow = 30 lb/s

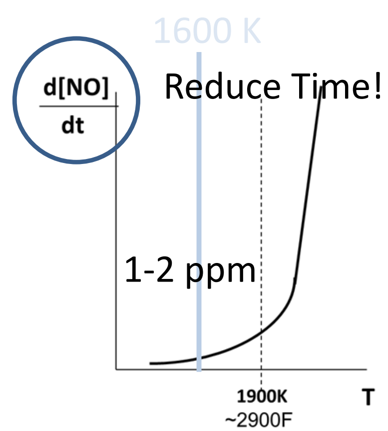




- **Lean Premixed Hydrogen "micromixers"**

Fuel + Air
Massflow = 30 lb/s





Micromix allows creative staging to attain turndown

Current Strategies

- **Micromix strategies adopted by GE, MHI (and others) 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).

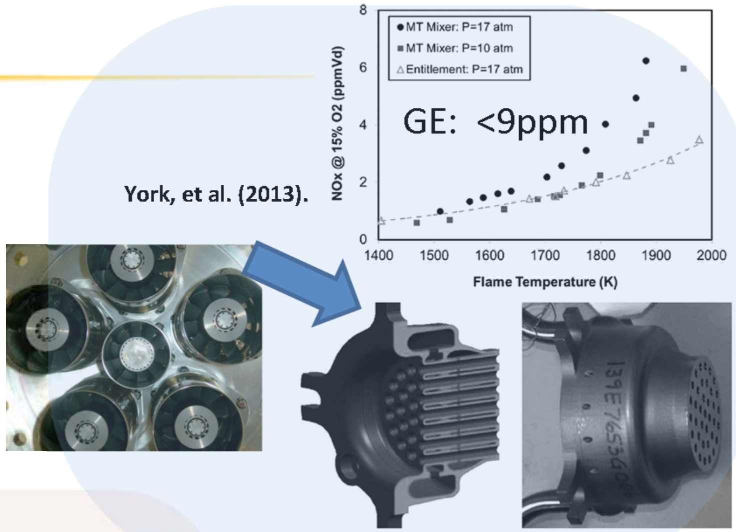
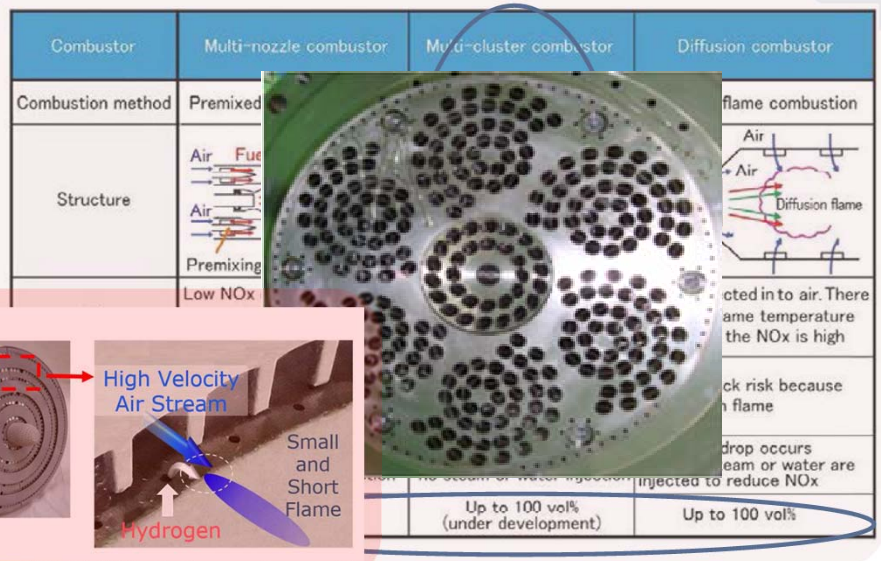
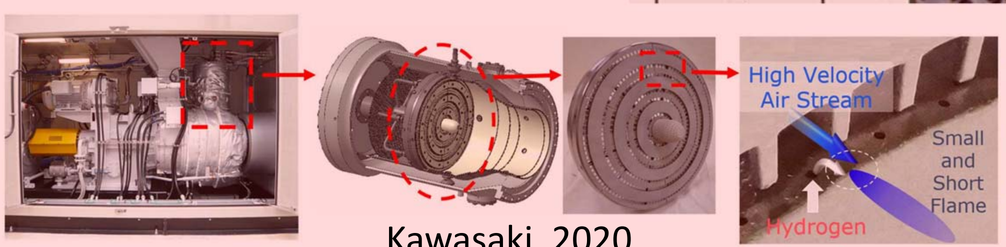


Fig. 2 Model cross section and photograph of small multitube mixer for high-hydrogen fuel

MHPS

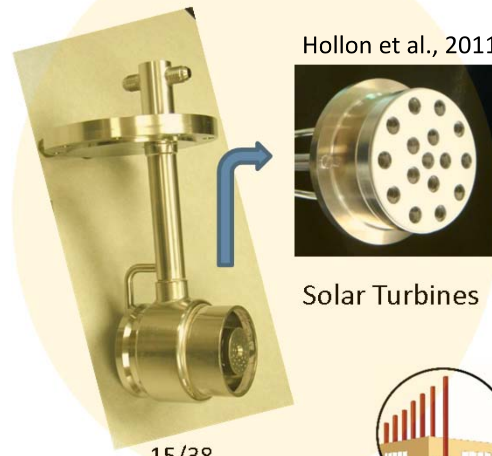


MHPS (2019). H_2 Power Generation Handbook



Kawasaki, 2020

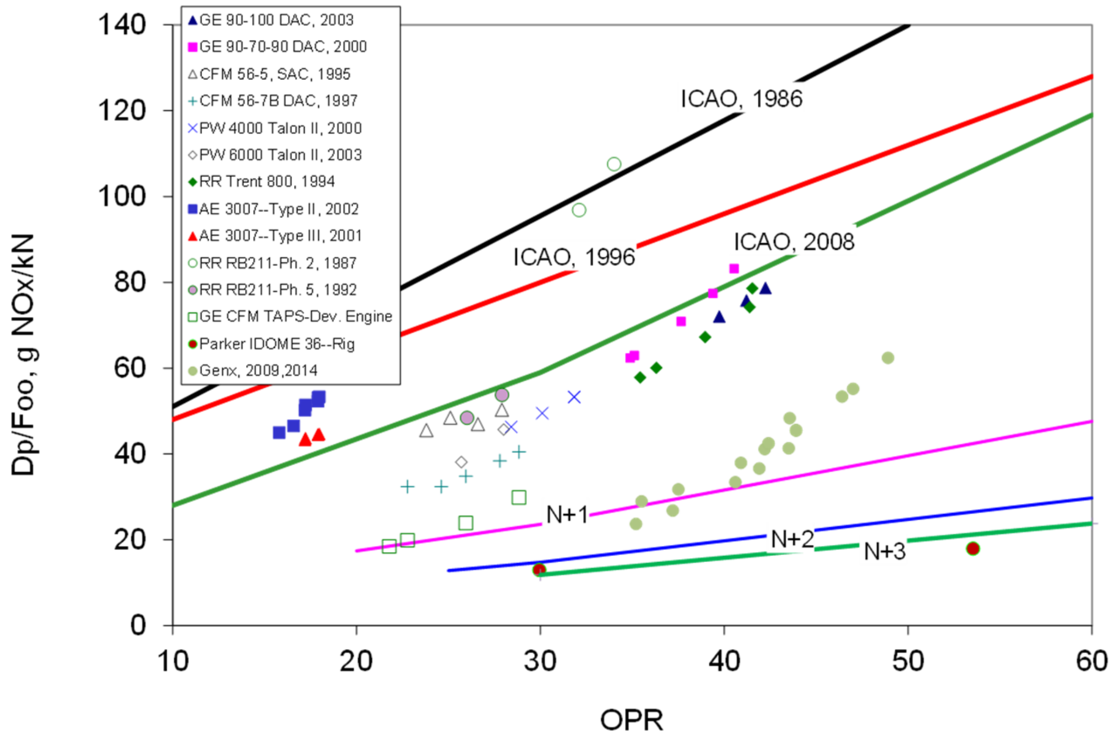
Hollon et al., 2011

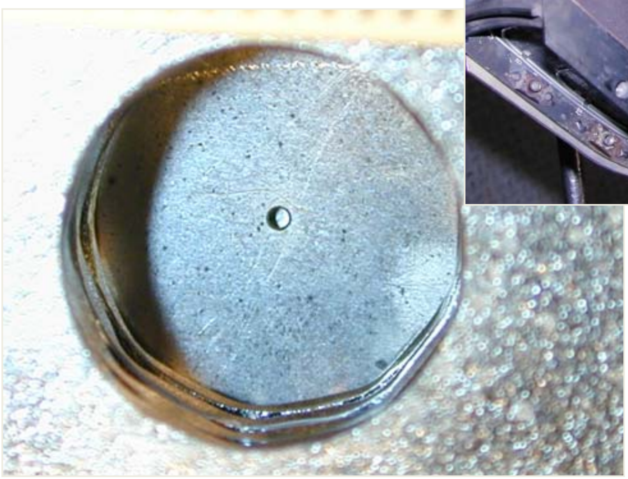


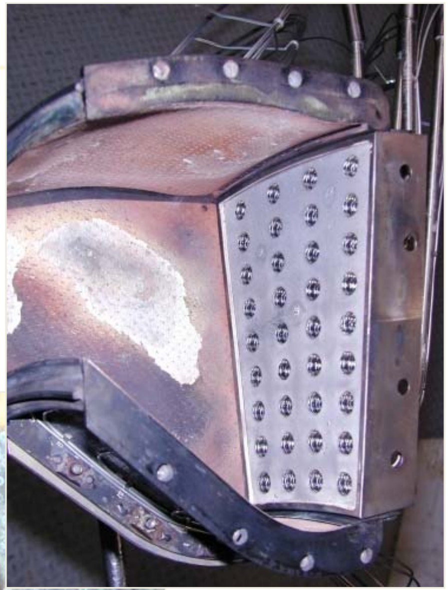
Solar Turbines

Prior Work

- **Aeroengine Context***





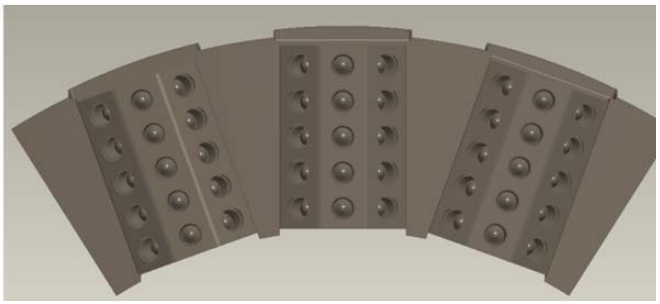


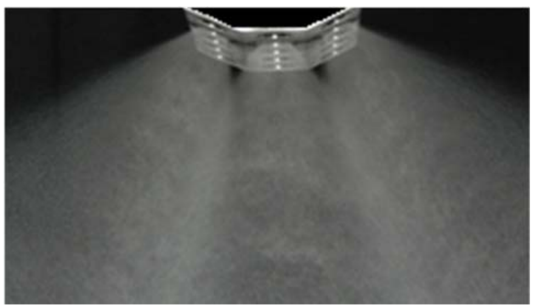
* McDonell, V.G. (2021). Emissions Reduction Technologies for Large Engine—UCICL Gas Turbine Combustion Short Course

Prior Work

- **Aeroengine Context**

Parker





Collins

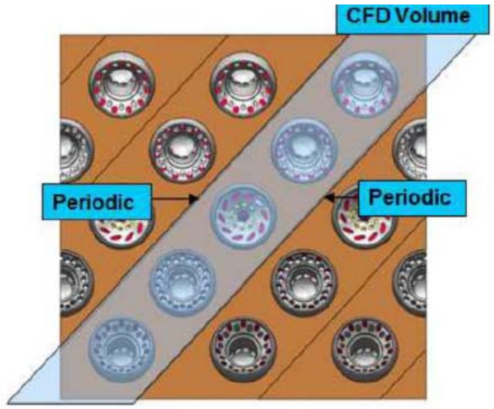
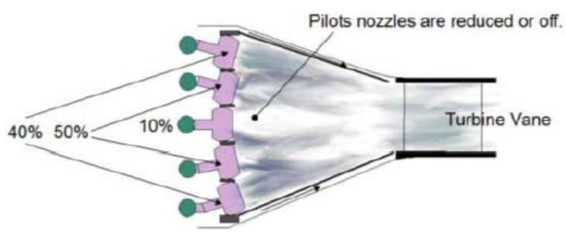
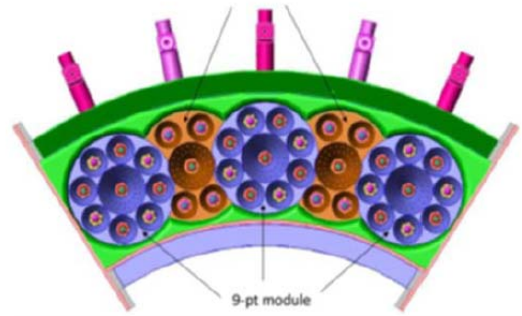


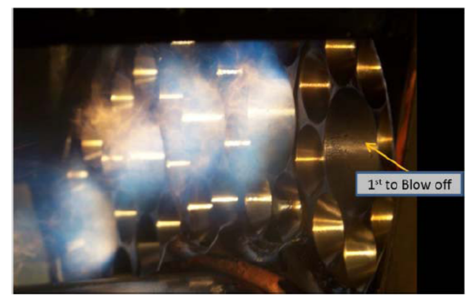
Figure 12 CFD assessment strategy. From ref. [2]



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

Woodward

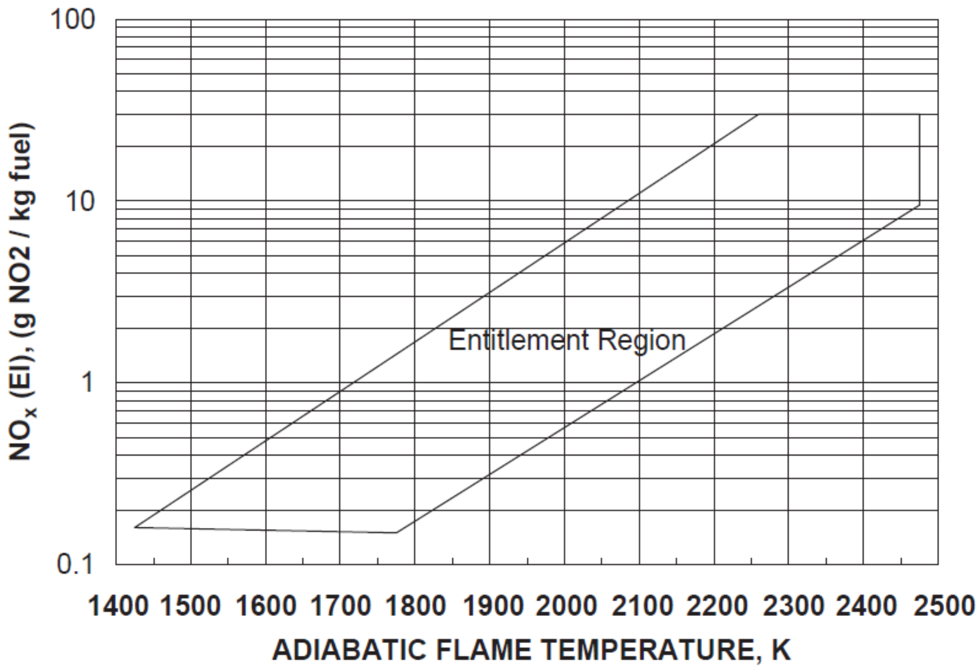


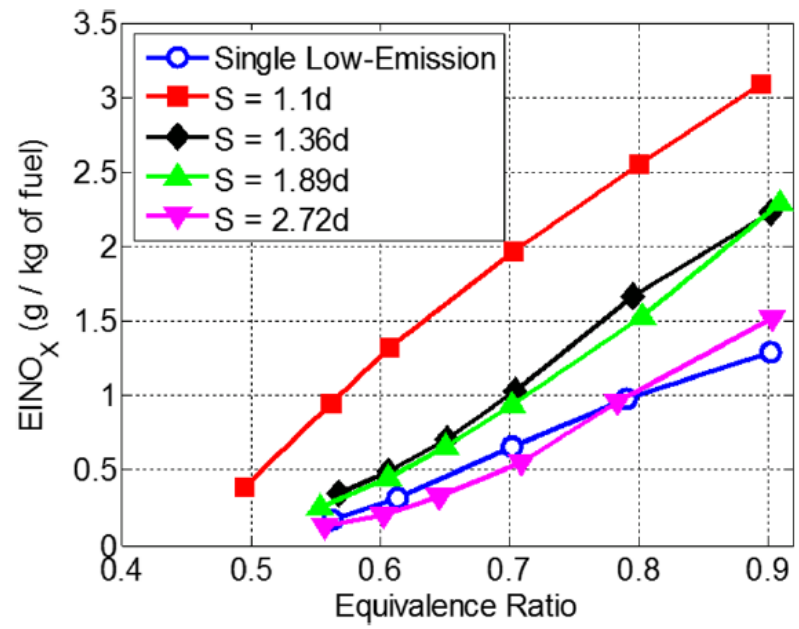


* C.M. Lee, C. Chang, S. Kramer, and J. Herbon (2013). NASA project develops next generation low-emissions combustor technologies, Paper AIAA-2013-0540

Prior Work

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



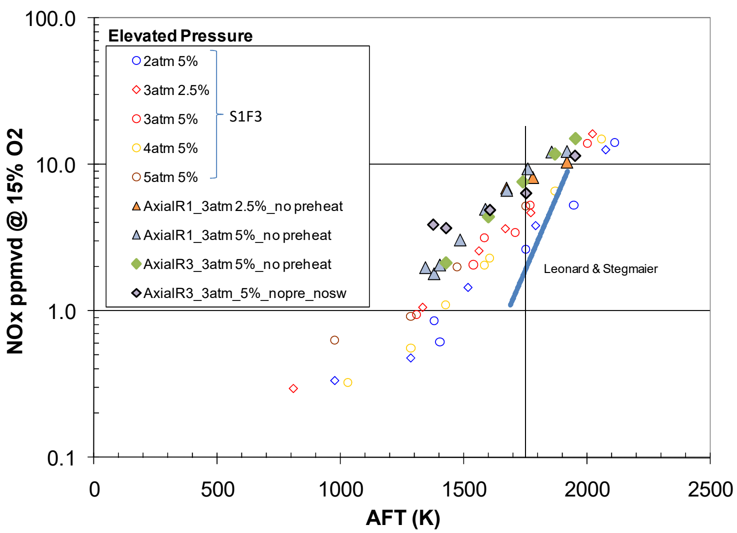


Tacina, R. (1990). Low NOx Potential of Gas Turbine Engines, Paper AIAA-90-0550, 28th Aerospace Sciences Meeting, Reno NV.

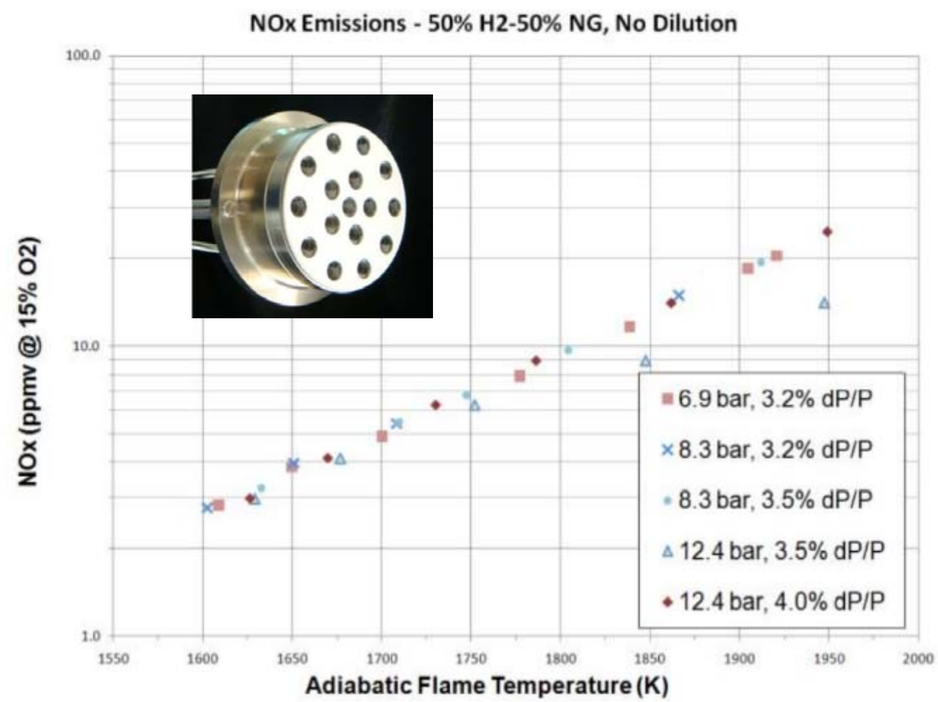
Dolan, B., Gomez, R., Zink, G., Pack, S., Gutmark, E., (2016). Effect of Nozzle Spacing on Nitrogen-Oxide Emissions and Lean Operability, AIAA Journal, Vol. 54(6), pp 1953-1961.

Prior Work

- **Adaptation for hydrogen fuels**



Lee, H., Hernandez, S., McDonell, V., Steinthorsson, E., Mansour, A., and Hollon, B. (2009). Development of Flashback Low-Emission Micro-Mixing Fuel Injector for 100% Hydrogen and Syngas Fuels, Paper GT2009-59502, Turbo EXPO 2009, Orlando FL



Hollon, B., Steinthorsson, E., Mansour, A., McDonell, V., and Lee, H. (2011). Ultra-Low Emission Hydrogen/Syngas Combustion With a 1.3MW Injector Using a Micro-Mixing Lean-Premix System, Paper GT2011-45929, ASME TurboExpo 2011, Vancouver

Prior Work

- **Prior work has established potential for micromix concepts but questions remain and an option between conventional scale and micro scale may be beneficial to consider**

Outline

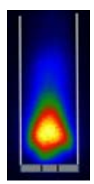
- Background
- Project objective(s)
- **Technical approach**
  - o **Team**
  - o **Tasks**
  - o **Schedule**
- **Next Steps**

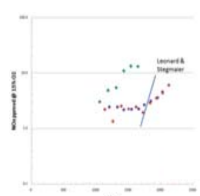
Objectives

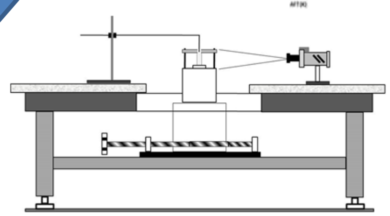
- **The proposed work will**
  - **1) <u>adapt</u> advanced liquid fuel injectors designed by Collins Aerospace for aero engines to accommodate injection of hydrogen/hydrogen natural gas blends and <u>screen</u>**
  - **2) <u>demonstrate</u> their operation using experiments from laboratory scale model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

Jet Fuel→Hydrogen

Screen

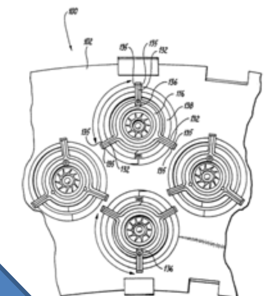


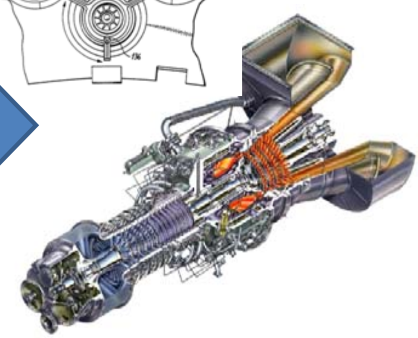




Demon strate

Design



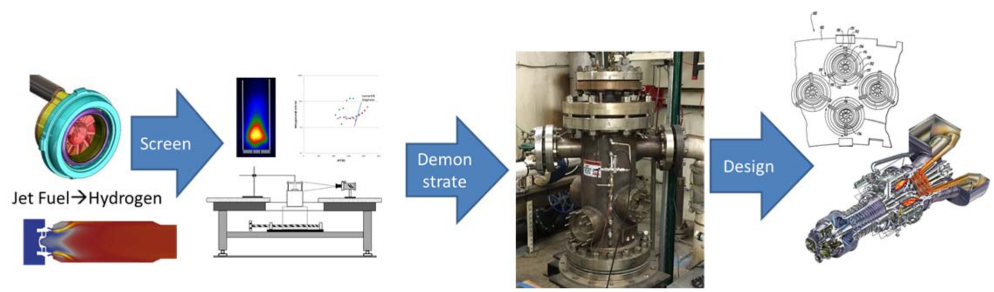


Outline

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

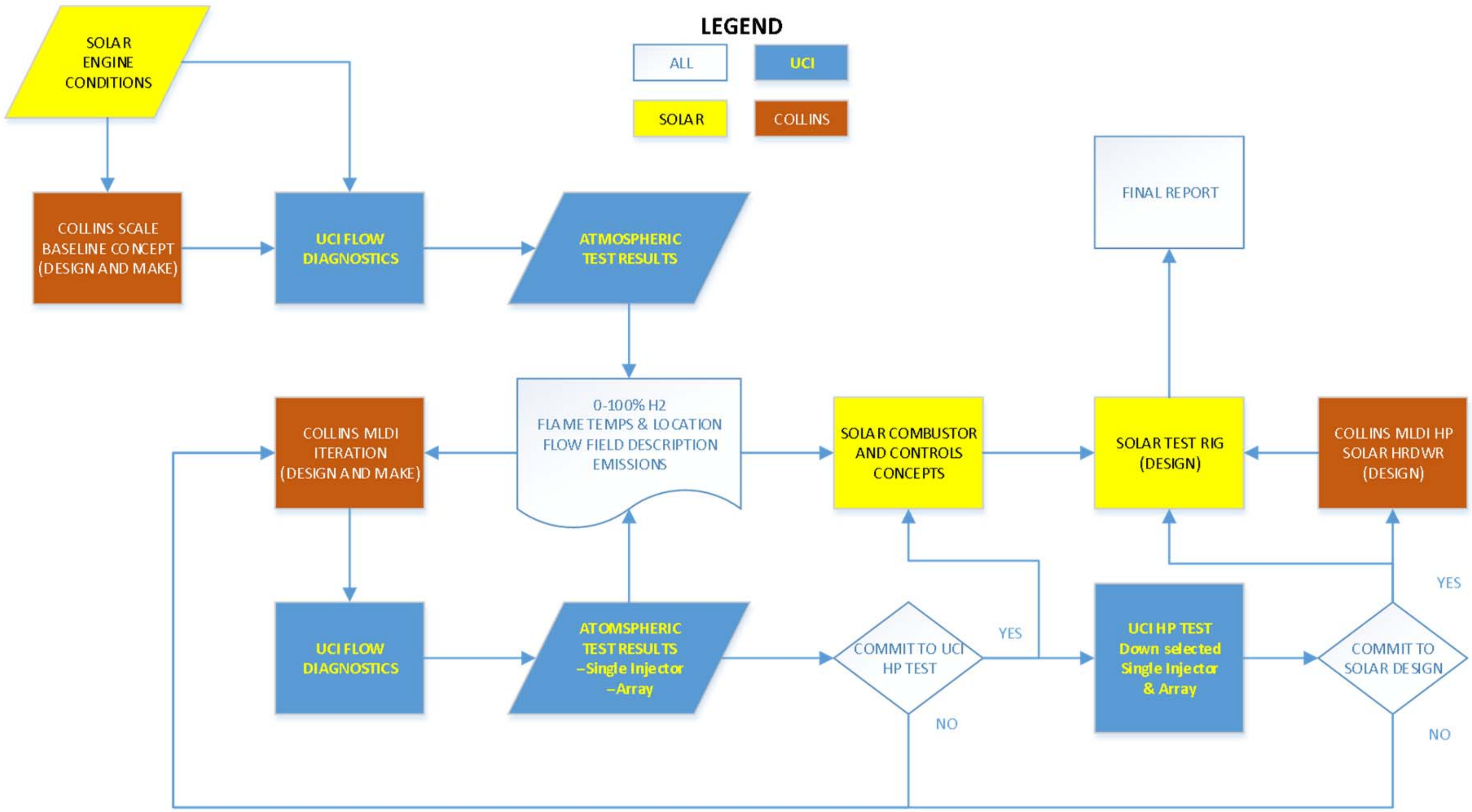
Technical Approach

- **General Approach**
  - Solar provide guidance on engine targets
  - CA migrate designs for liquid LDI concepts to accommodate hydrogen
    - ✓ Computational Fluid Dynamics to guide
    - ✓ Facilitate parametric study
    - ✓ Facilitate documentation of boundary and inlet conditions
    - ✓ Statistically designed experiments approach
  - UCI experimentally screen individual injector concepts at atmospheric conditions w/preheat
    - ✓ Lean Blow off
    - ✓ Ignition
    - ✓ Flashback
    - ✓ Flame Structure
    - ✓ Emissions
  - CA Develop arrays from promising concepts
  - UCI Evaluate at up to 10 atm
  - Design for test rig at Solar Turbines



Technical Approach

- **Team**



Schedule and Budget

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
1--Project Management												
2—Test Plan Development (All)												
3—Hardware Development (CA)											Design only	
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)	*	*	*	*	*	*	*	*	*	*		

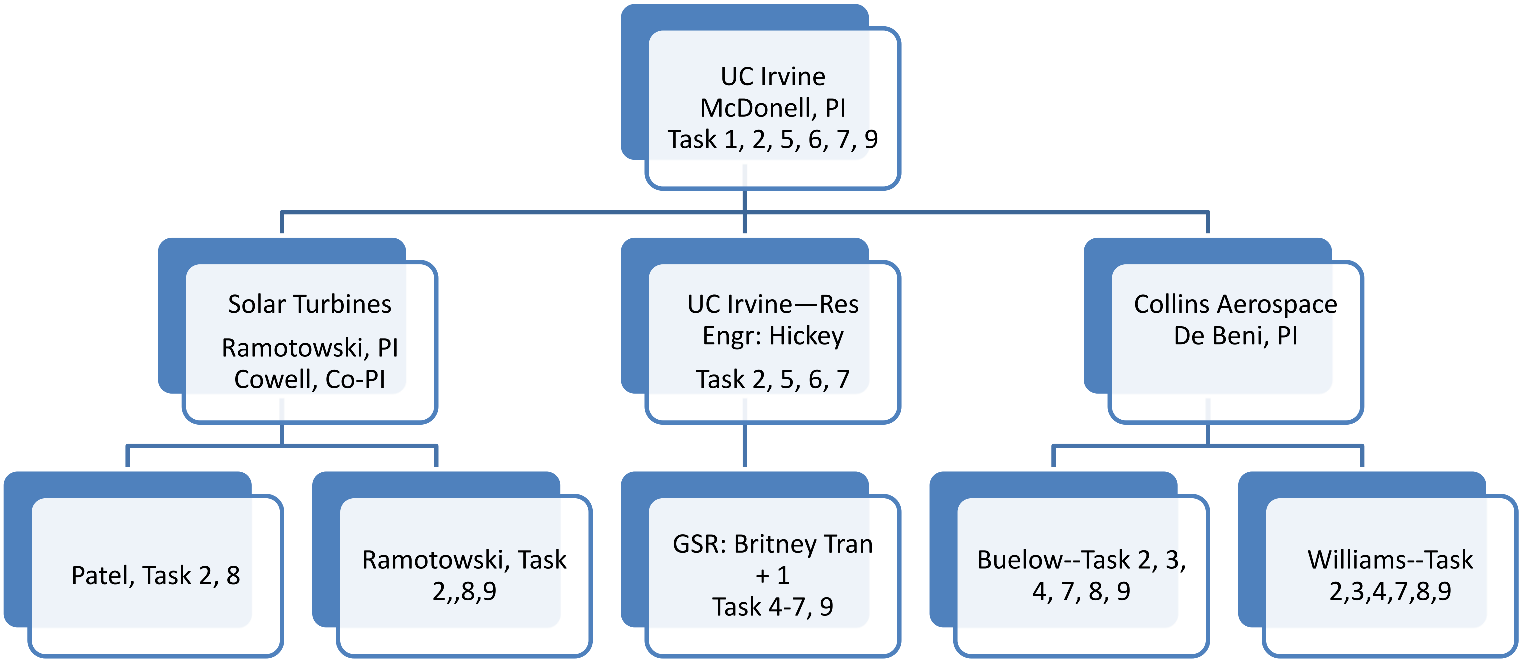
Milestones
--Test Plan Report
--UCI Test Report—1 atm
--UCI Test Report—10 atm
--Solar Design Report—Included in Final Report

--Quarterly Reports
--Final Report

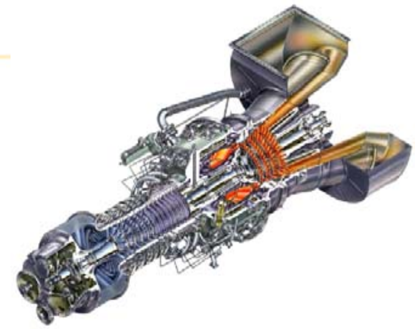
DOE: $800,000
Cost Share: $200,00

Project Management Plan

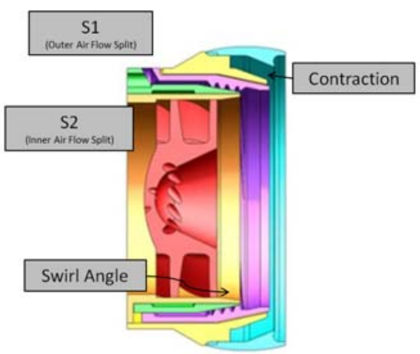
- **Organization**



Technical Approach



- Task 2—Test Plan Development
  - Informed by target Solar engine platform
    - ✓ Sets conditions of interest and basic injector building block scale
  - Parameter space of interest



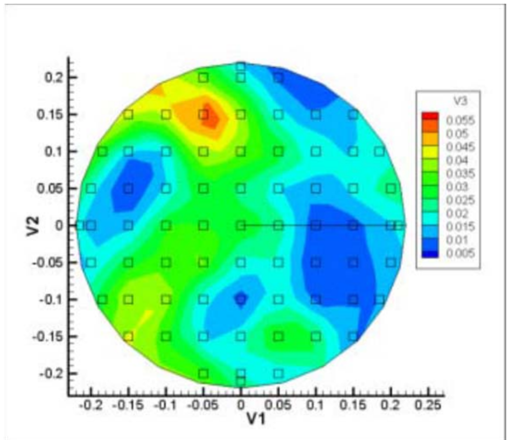
	Minimum	Maximum	Comment
Parameter			
1--S1/S2 flow split	40/60	60/40	Hardware configuration
2--Swirl Angle, deg	30	60	Hardware configuration
3--Contraction, r/R	r/R = 0.8	r/R = 0.6	Hardware configuration
4--Temperature, K	500	800	Flow condition
5--Pressure Drop, %	2	4	Flow condition
6--%H2 in NG	0	100	Flow condition to establish operation range
Fuel to Air Ratio	LBO	Near stoichiometric	Flow condition to establish operation range
Inlet Pressure	1 atm	10 atm	Task 5—1 atm, Task 6—up to 10 atm

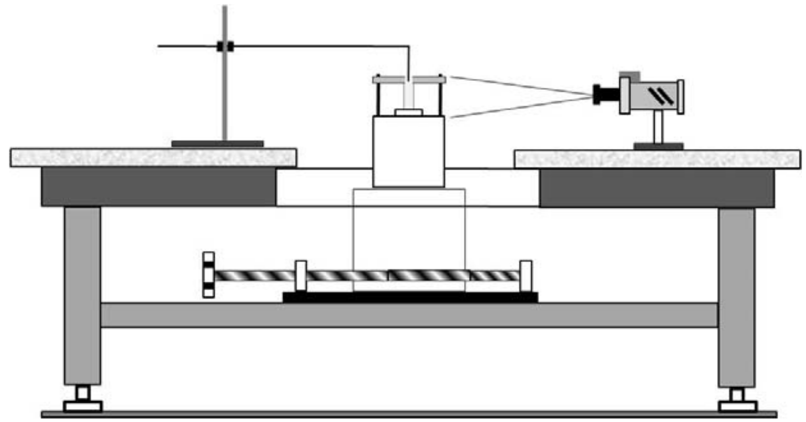
- ✓ 3 geometric parameters
  - – Three level full factorial design: 27 configurations
  - – Fractional factorial design can reduce number of configs built
- ✓ 3 flow parameters

54 or 56 test points
(Box-Behnken or I-Optimal Design)

Technical Approach

- **Task 2—Test Plan Development**
  - **Diagnostics**
    - ✓ **F/A Mixing**





- ✓ **OH* for flame structure**
  - – **Stability/LBO**

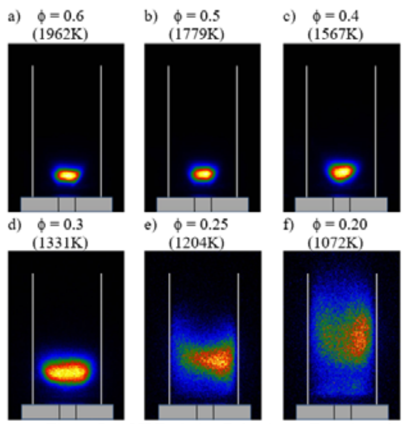
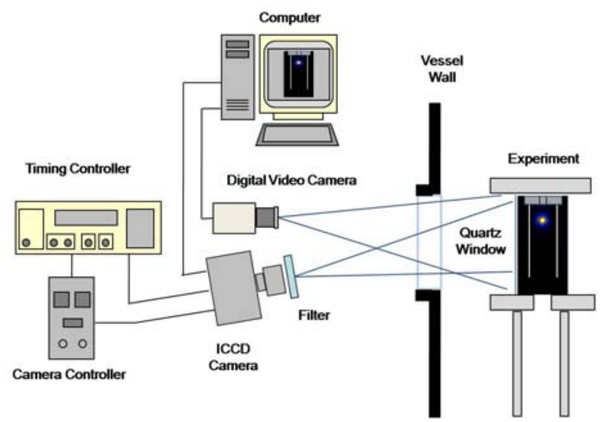


Figure 7. OH Emission Behavior as Function of Equivalence Ratio for Hydrogen (1.6% DP/P).



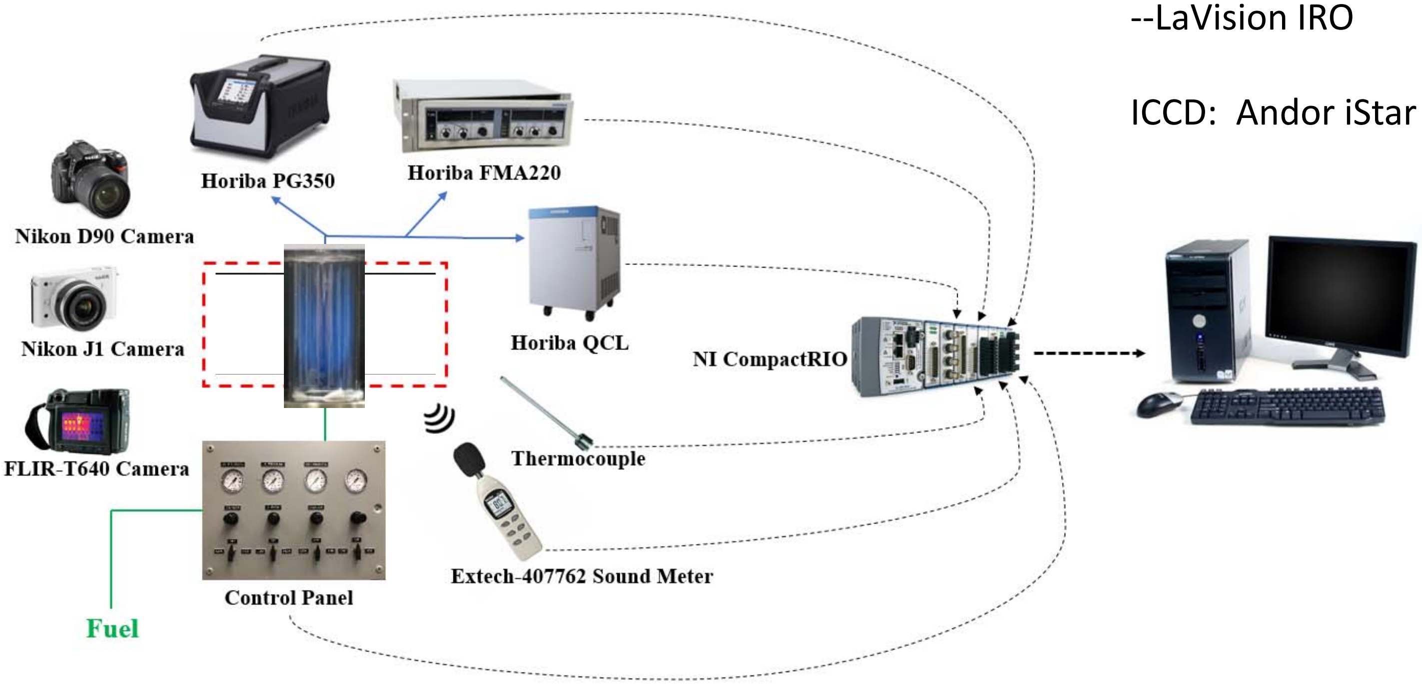
Technical Approach

- **Task 2– Test Plan Development**
  - ✓ **Emissions/Other**

NO, NO_2, CO, UHC, NH_3, N_2O, CO_2, O_2

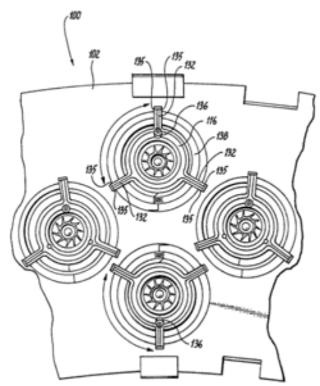
Intensified High Speed Camera
--Photron Nova / Phantom 7.2
--Lambert Intensifier
--LaVision IRO

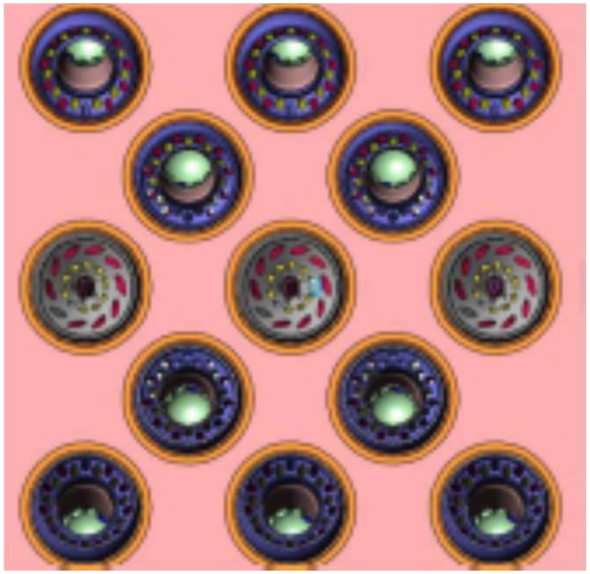
ICCD: Andor iStar



Technical Approach

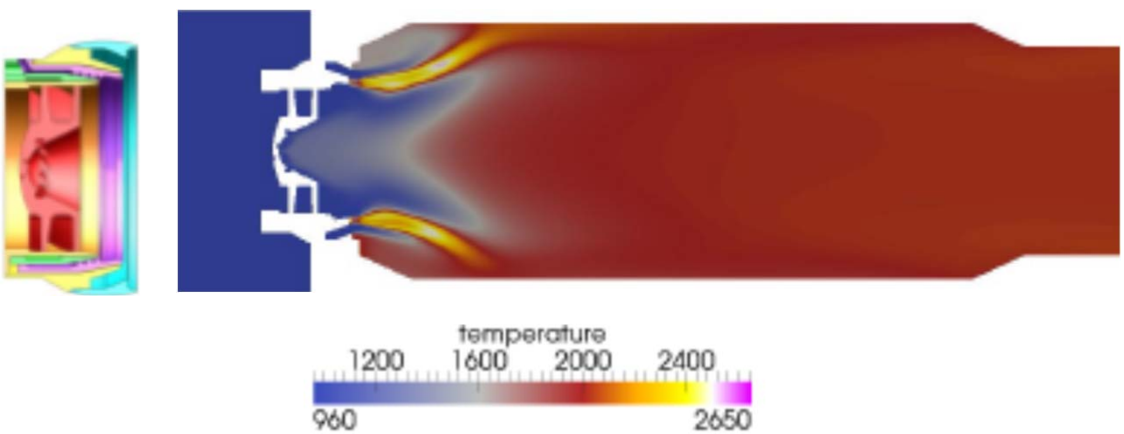
- **Task 3—Hardware Development (Collins Aerospace)**
  - **3.1 Fabricate single injector configurations based on Test Plan**
    - ✓ **AM concepts**
  - **3.2 Fabricate 2-3 arrays based on results from single injector tests**

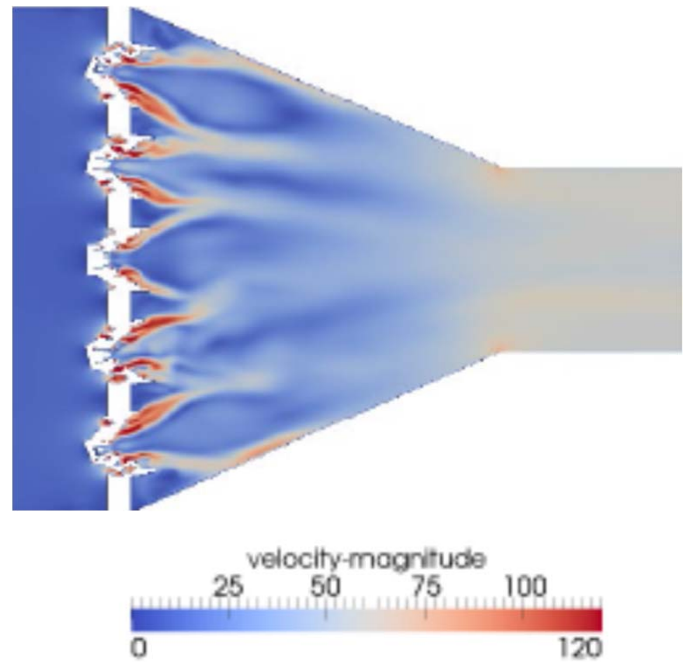




Technical Approach

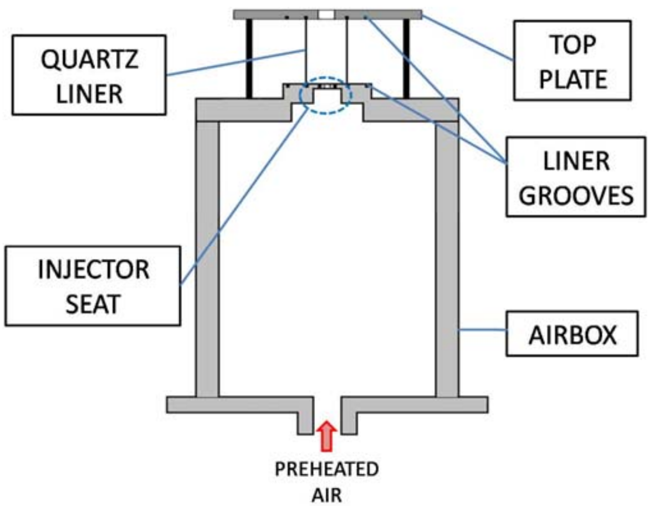
- **Task 4—Simulation Support (Collins/UCI)**

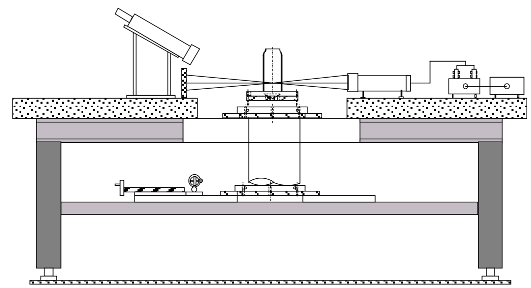


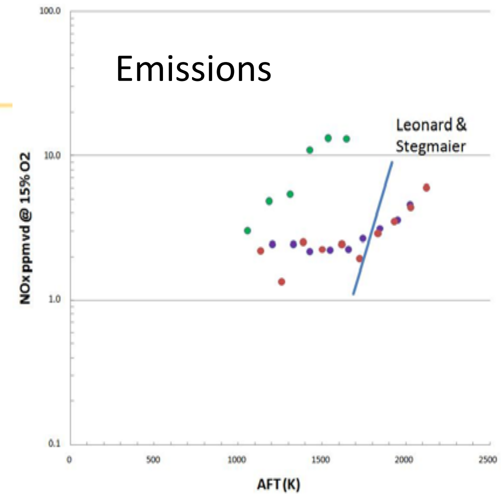


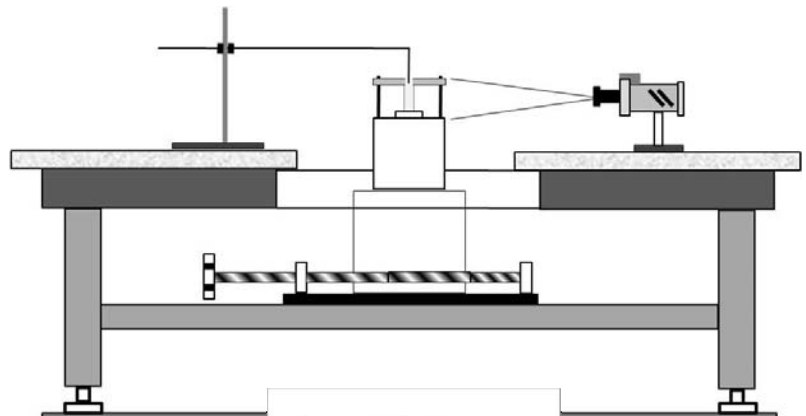
Technical Approach

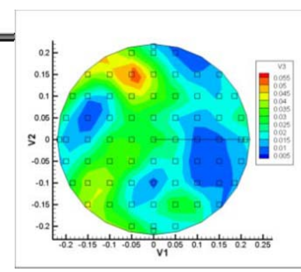
- **Task 5—Atmospheric Tests (UCI)**











F/A Mixing

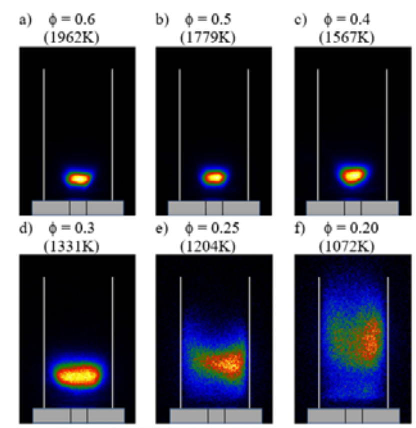
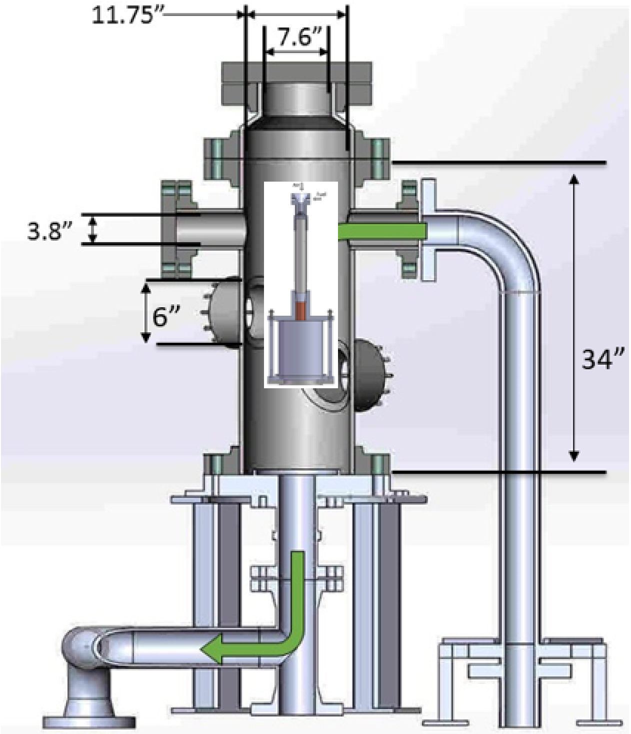


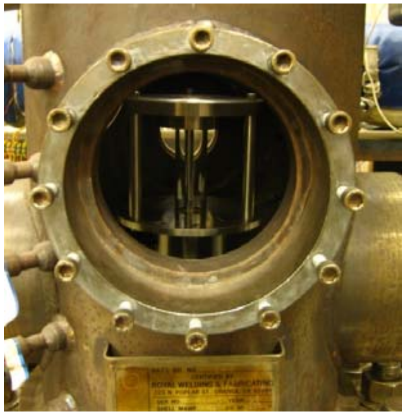
Figure 7. OH Emission Behavior as Function of Equivalence Ratio for Hydrogen (1.6% DP/P).

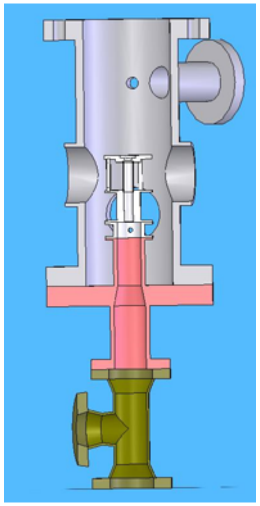
Flame Structure
LBO

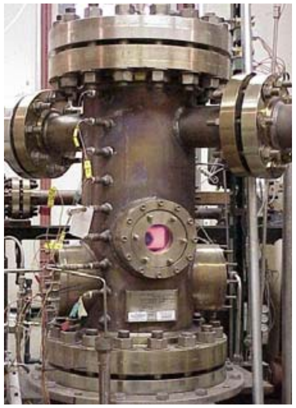
Technical Approach

- **Task 6—High Pressure Tests (UCI): ~up to 10 atm, 800 K**
  - **Single Module**



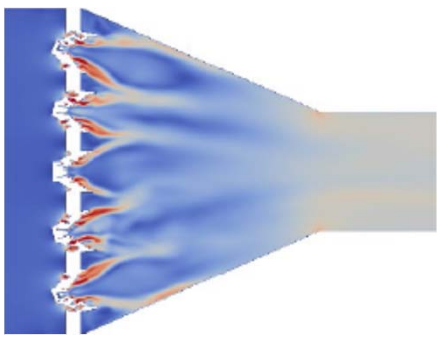


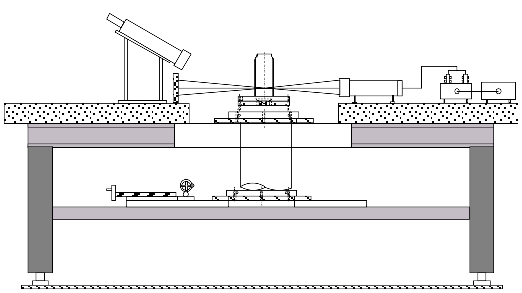


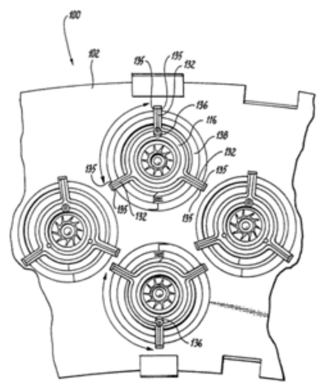


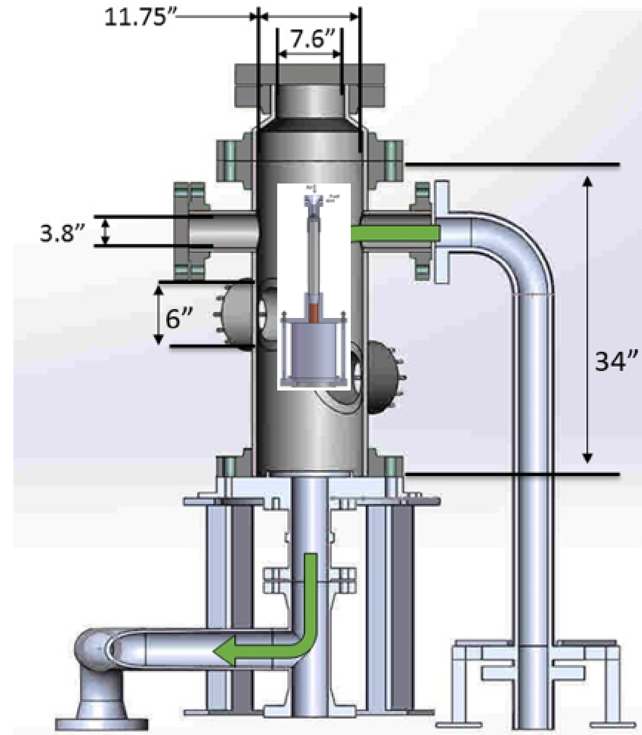
Technical Approach

- **Task 7—Array Tests (UCI)**
  - **Collins: CFD design**
  - **Check injector to injector spacing**



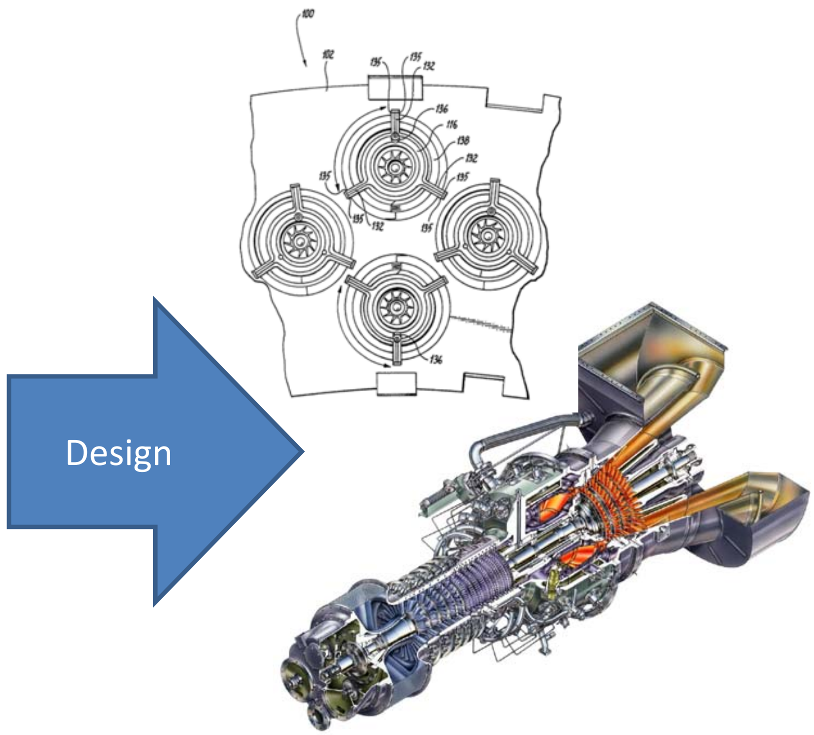






Technical Approach

- **Task 8—Design for Solar Test Rig (Collins/Solar)**



Outline

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

Next Steps

- Finalize Test Plan
- Finalize initial hardware configurations
- Prepare 1 atm stand
- Prepare diagnostics