Optimizing the CSP Tower Air Brayton Cycle System to Meet the SunShot Objectives

Southwest Research Institute

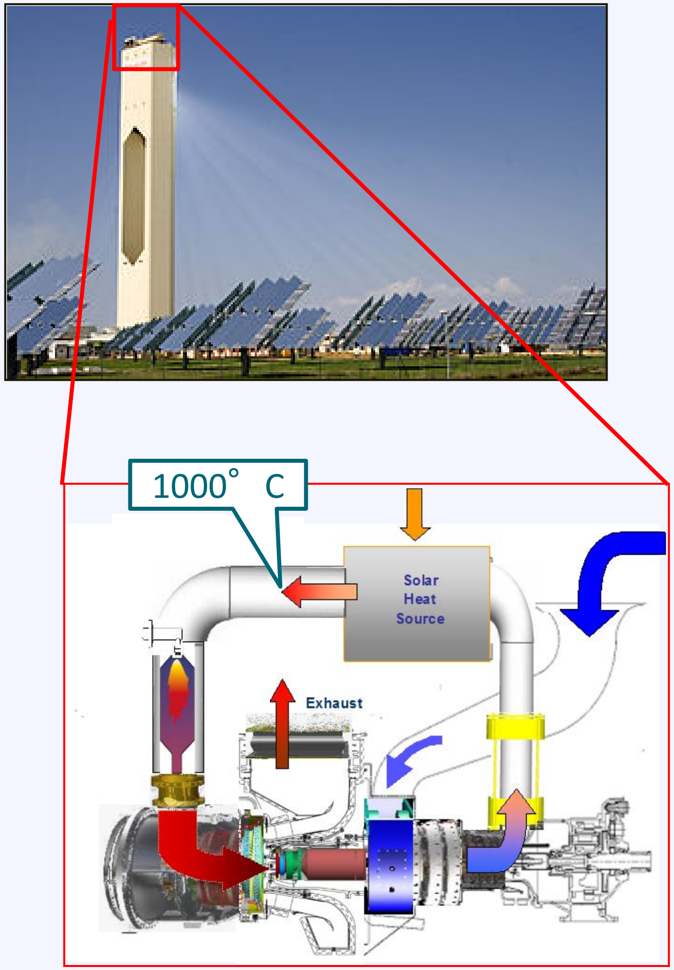
Solar Turbines, Inc.

Oak Ridge National Laboratory

German Aerospace Center (DLR)

Klaus Brun, PhD (SwRI)

Shane Coogan (SwRI)



Micromix Combustor for High Temperature CSP Air Brayton Cycle Systems

- Project description
  - Technology baseline
  - Objectives
- Challenges of the high temperature environment
  - Shortcomings of conventional combustors
  - Requirements for a new design
- Micromix combustor solution
  - Design description
  - Analysis summary
- Current and future work

Technology Baseline

- Solugas air Brayton CSP / gas turbine project in Spain represents the state-of-the-art
  - Maximum solar receiver temperature of 800 °C
  - Maximum combustor inlet temperature of 650 °C
- These temperatures need to be increased to 1,000°C to meet SunShot LCOE objective.
  - No system currently exists to meet this need.
- Beneficial research area
  - Some common ground with hydrogen combustion.
  - Unique challenges specific to the CSP application.

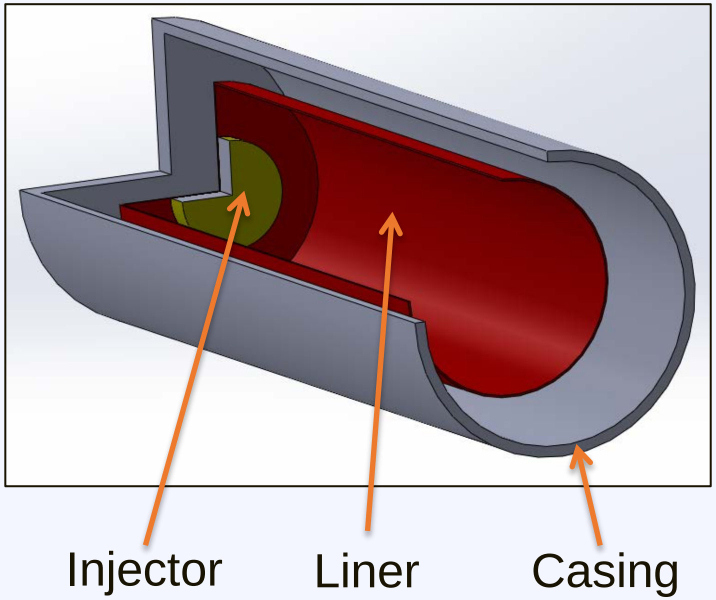
Novel high temperature CSP combustor solution is needed.

Project Objectives

- Develop a natural gas combustor for high temperature CSP applications.
  - Accept inlet air over the range of 600-1,000°C.
  - Compatible with Solar Turbines Mercury 50 gas turbine (unit installed in the Solugas facility).
- Project will take technology from TRL 3 to a full TRL 6 (MW-scale prototype demonstration).

Design Scope

1.5 MW Can Combustor



Project Structure

Phase 1 (9/12 – 9/13)
•Concept evaluation
•Combustor design
•Test facility design

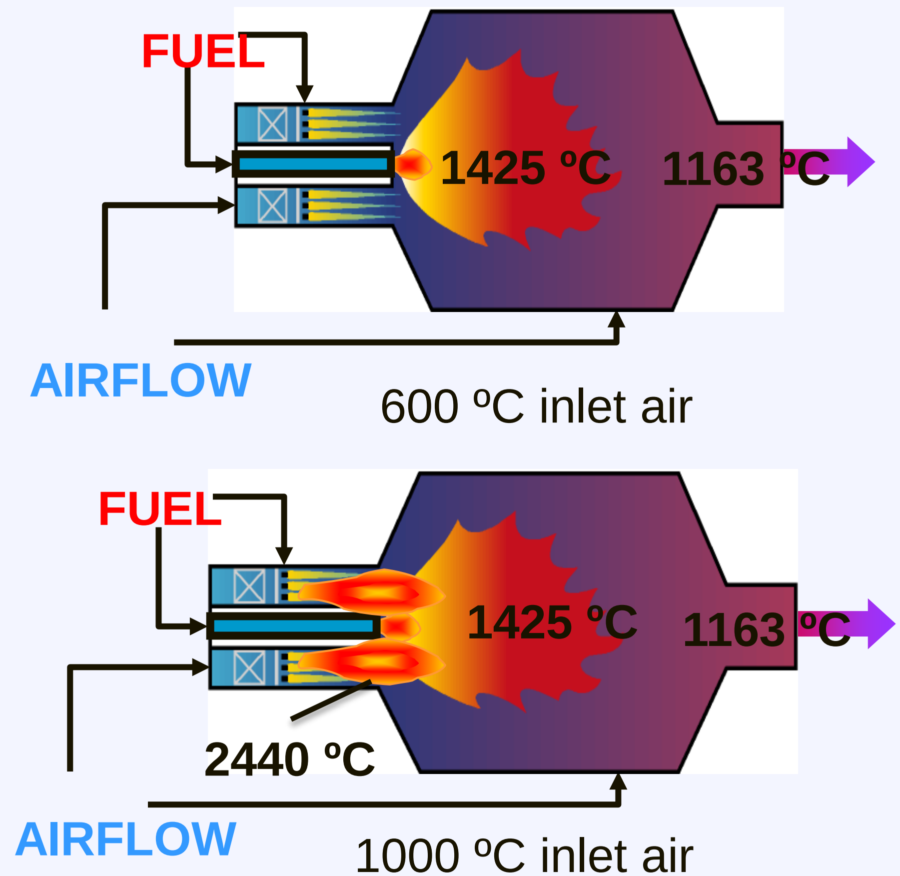
Phase 2 (12 months)
•Combustor fabrication
•Test facility fabrication

Phase 3 (3 months)
•Testing

Shortcomings of Conventional Combustors

- Modern industrial gas turbines use lean pre-mixing injection to control emissions.
  - Low flame temperature limits NO_x production.
- At 1,000°C for natural gas (or lower temps for almost all other fuels), ignition will occur before pre-mixing is complete in a conventional combustor design.
  - High emissions from stoichiometric zones.
  - Damage to pre-mixing chamber.
  - Result of **autoignition** and **flashback**.

Pre-mix Combustor Operation



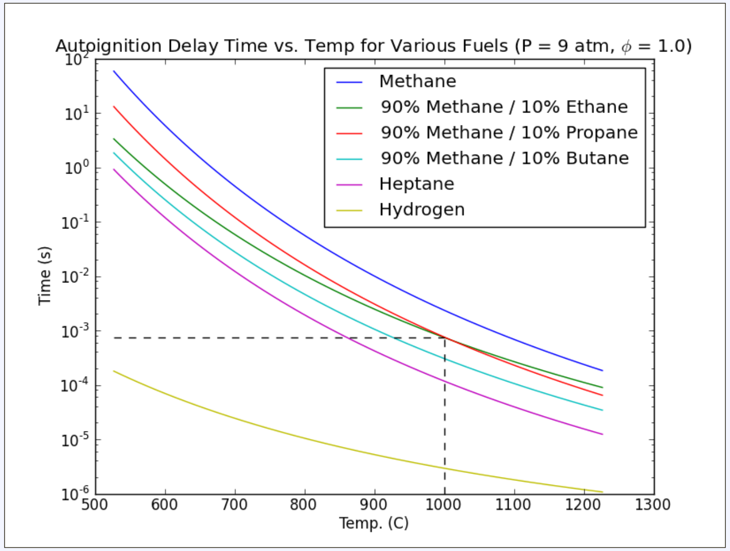
Base images courtesy of Solar Turbines.

SunShot U.S. Department of Energy

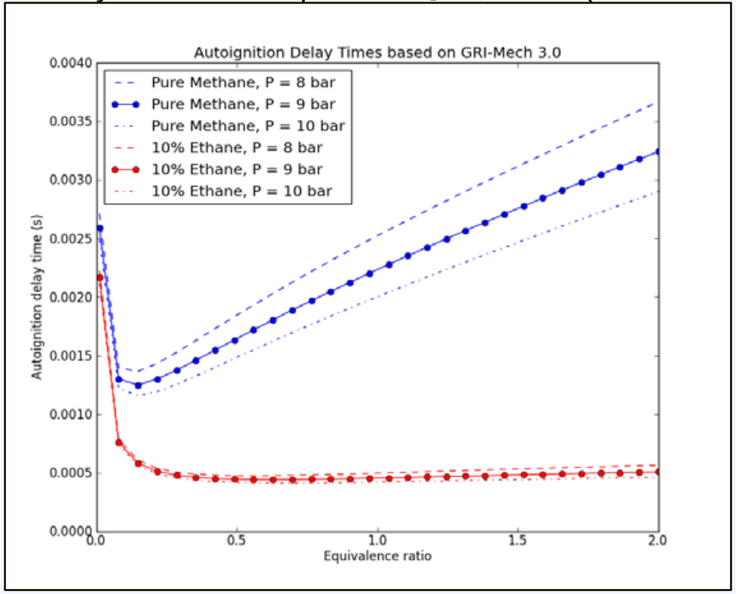
Design Requirements: Autoignition

- Autoignition delay is 3 orders of magnitude shorter than in conventional turbines.
  - Conventional: $t_{delay} >> t_{residence}$
  - Now: $t_{delay} << t_{residence}$
- Design to minimum possible ignition delay time.
  - 0.4 ms for 10% ethane @ 10 bar
  - Use 0.2 ms because of scatter in experimental data.
- Longer residence regions (boundary layer) must be kept extremely <u>lean</u>.
  - Delay time increases sharply at low equivalence ratios.

Autoignition delay time vs. temperature (lit. correlations[1,2])



Autoignition delay time vs. composition @ 1,000ºC (detailed kinetics)

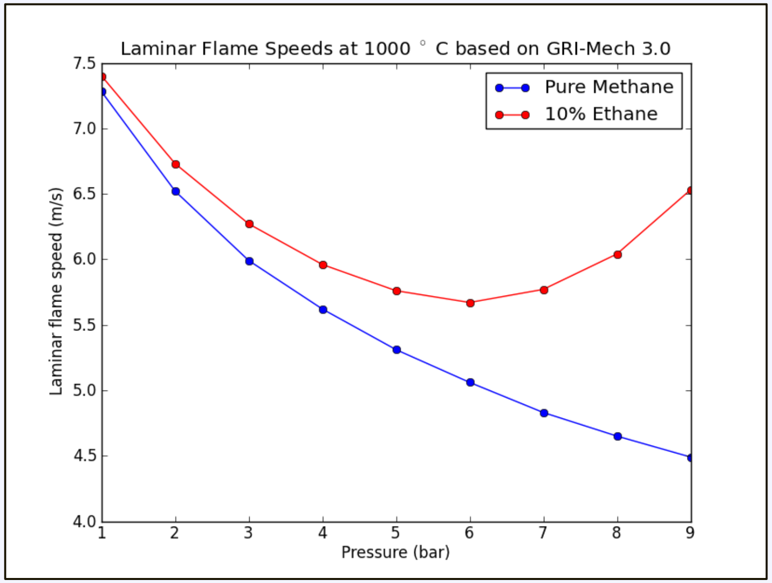


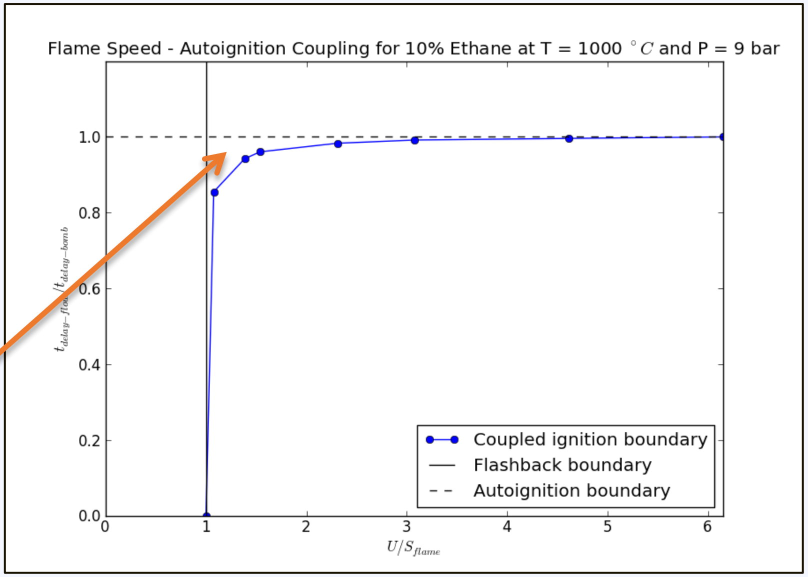
<u>References</u>

1. L. J. Spadacinni and M. B. Colket, "Ignition Delay Characteristics of Methane Fuels," *Progress in Energy and Combustion Science*, Vol. 20 No. 5, pp. 431-460, 1994.
2. M. B. Colket and L. J. Spadacinni, "Scramjet Fuels Autoignition Study," Journal of Propulsion and Power, Vol. 17. No. 2, pp. 315-323, March-April 2001.

Design Requirements: Flashback

- The minimum injector velocity must exceed the flame speed.
  - Prevent flashback.
- Maximum laminar flame speed for this application = 6.5 m/s.
  - 20 fold increase over room temperature value
- Flame propagation and autoignition mechanisms interact over a certain velocity range.
- Time-of-flight autoignition delay is less than the stationary autoignition delay (such as from shock tube experiments).
  - Flow velocity needs to be 3 times greater than flame speed to avoid coupling.

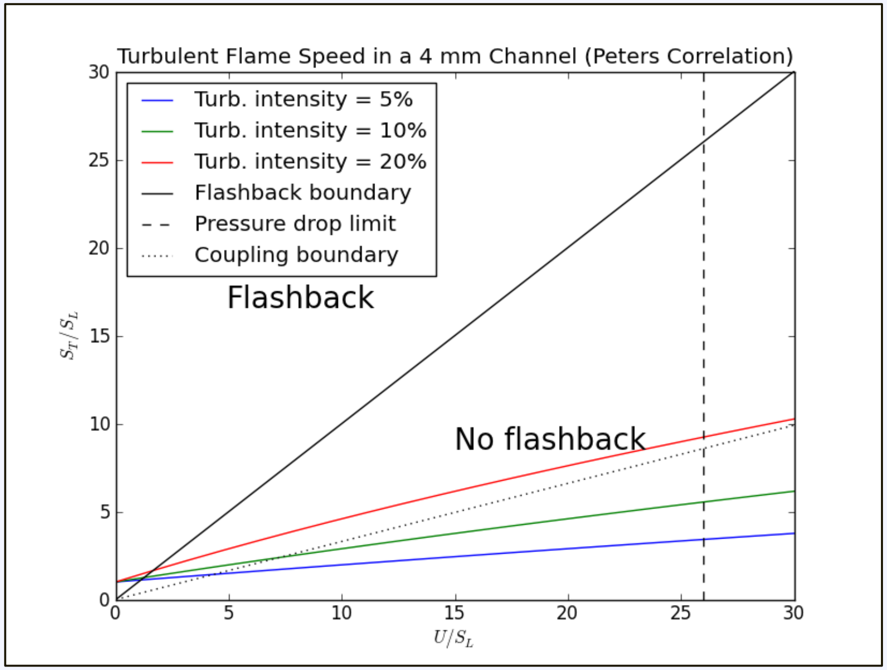




New ignition region not indicated by flame speed or autoignition alone.

Design Requirements: Injector Summary

- Relevant flame speed is the turbulent flame speed (S_T) rather than the laminar flame speed (S_L)
  - Complicated - depends on turbulent structure and the chemical time scale.
- Turbulent speed is always faster than the laminar speed.
  - Turbulent velocity fluctuations will increase with flow speed.
  - Therefore, the turbulent flame speed will increase with flow speed.
- Need to ensure a viable premix solution is possible.
  - Viable design space defined by the flashback and pressure drop limit boundaries.
  - Design outside of the coupling boundary is also desired.
- Optimal solution identified at U/S_L = 15.
  - Injector hole flow velocity needs to be 100 m/s.



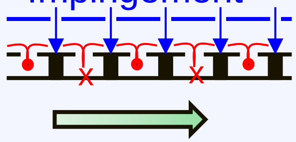
Summary of Injector Requirements

- Premixing must be accomplished in 0.2 ms.
- Injector velocity should equal 100 m/s.
- Fuel must be minimized in boundary layers.

Design Requirements: Cooling and Airflow

<u>Preferred cooling at low inlet temperatures</u>

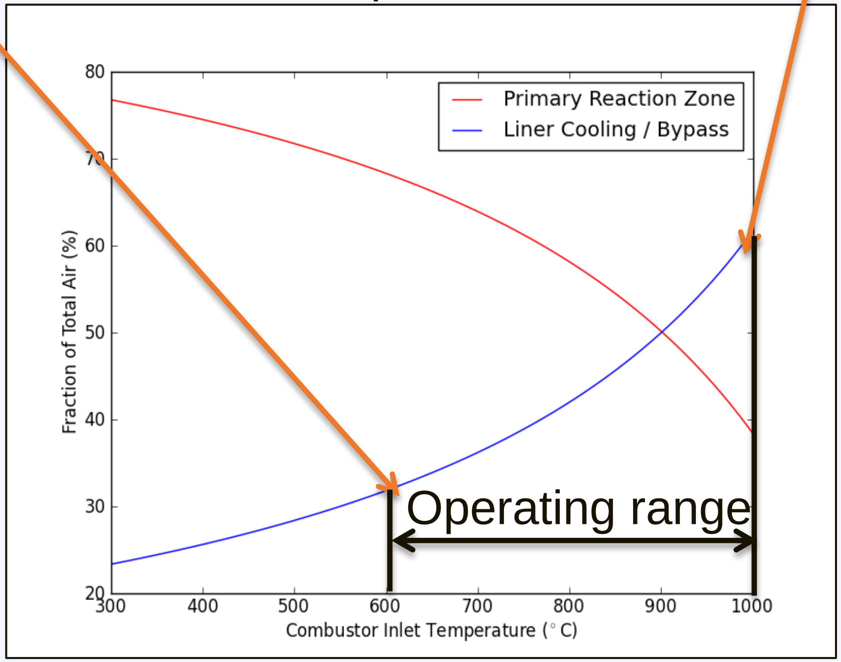
Impingement



Combustion gas

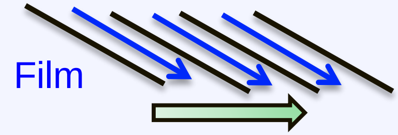
- Low quantity of cold air
  - Film cooling too inefficient
  - Cold air can quench CO reaction

Airflow requirements vs. inlet temperature



<u>Preferred cooling at high inlet temperatures</u>

Film



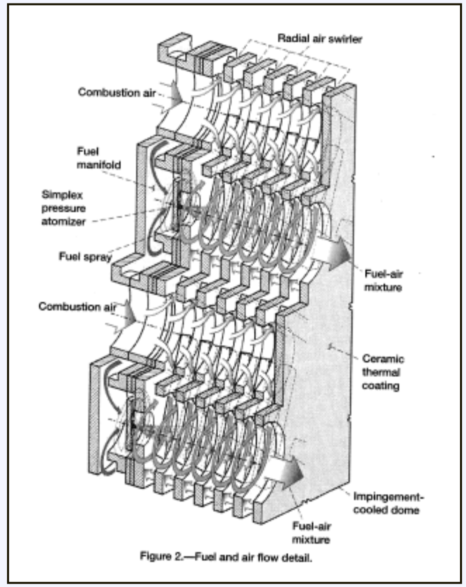
Combustion gas

- Large quantity of hot air
  - Less quenching risk
  - Liberal film cooling can bathe liner in coldest possible temperature

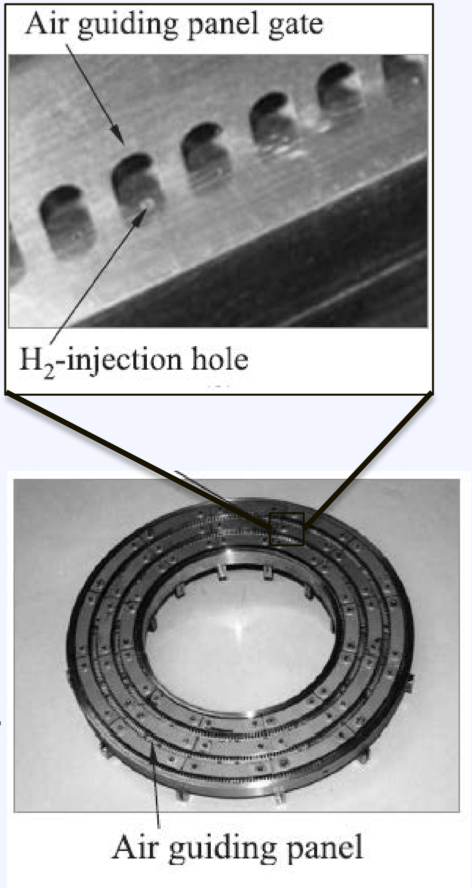
- System must be able to adjust the amount of primary zone air.
- Adaptive cooling is required to minimize material requirements.

Micromix Combustor Design

- Showerhead grid of small air/fuel injectors reduces mixing length scale.
- Complete mixing occurs more rapidly because of reduced scale.
  - Low emissions with reduced autoignition and flashback risk.
- Concept has been pursued for both liquid fuel and natural gas.
- Currently being researched for hydrogen combustion applications.



Liquid fuel micromix injector
NASA / Parker Hannifin



H_2 Injector
Boerner, et al.

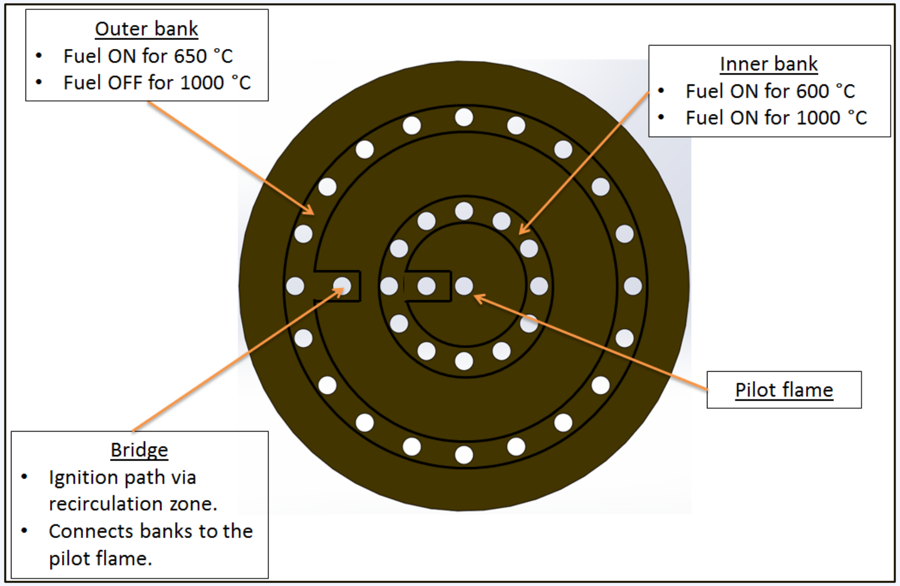
Micromix injector design addresses the autoignition and flashback issues of high temperature CSP systems.

References

1. R. Tacina, C. Wey, P. Liang, and A. Mansour, “A Low NOx Lean-Direct Injection, Multipoint Integrated Module Combustor Concept for Advanced Aircraft Gas Turbines,” NASA/TM-2002-211347, April 2002.
2. S. Boerner, et al., “Development and Integration of a Scalable Low NO_x Combustion Chamber for a Hydrogen-fueled Aerogas Turbine,” *Progress in Propulsion Physics*, Vol. 4, pp. 357-372, 2013.

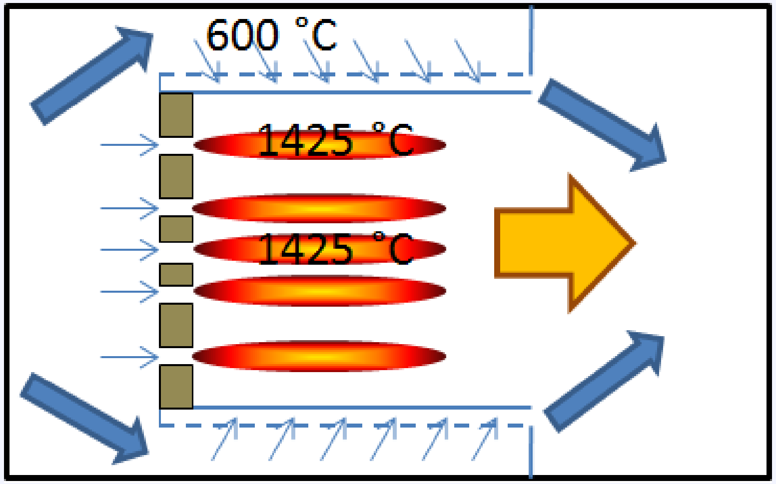
Micromix Combustor Design: Multibank Approach

- Two solutions to shifting airflow requirement problem
- Global bypass
  - Air is not available for cooling.
  - Refractory liner must be used.
- Adaptive liner
  - Air is locally rerouted from primary air to cooling channels.
  - Metallic liner may be used.
- Adaptive liner is preferred, but implementation must be simple.
  - Micro-mixing injector offers solution.

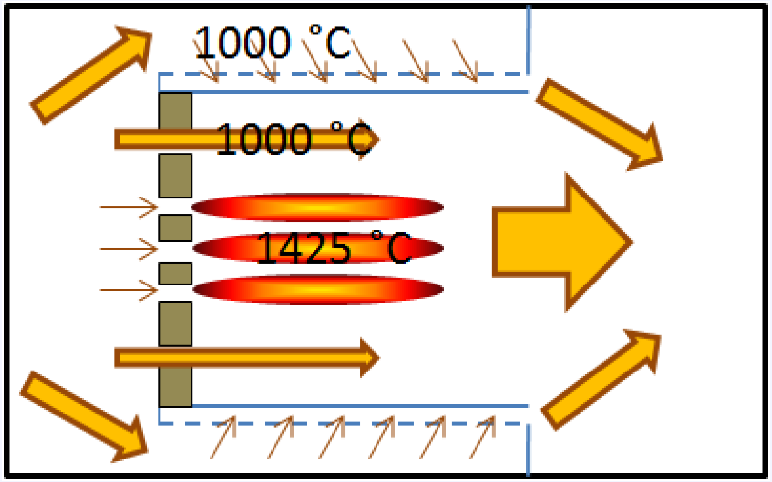


Injector port arrangement on micro-mix injector.

Micromix Combustor Design: Multibank Approach



600 ºC Operation



1000 ºC Operation

- Impingement or convection cooled liner provides baseline cooling
- Air split between liner and injector ports is fixed for all inlet temperatures.
- As inlet temperature increases, fuel to outer banks is shutoff.
- Combustion continues undisturbed in the inner bank.
  - Small flame dimensions compared to bank separation.
- Air flowing through the outer bank injector ports now protects liner from hot inner core.

- Multibank injector implements adaptive cooling with a mechanically simple design.
- Cooling approach enables the use of metallic materials.

Micromix Combustor Design: Mixing

- Micromix selection fixes the overall approach but leaves open the detailed fuel/air mixing design.
- Seek efficient but simple device for mixing two fluids
  - Consult the chemical engineering literature
- Tee mixer is highly effective and well documented
  - Jet in crossflow (JICF)
  - Complete mixing possible in a few pipe diameters
- Variety of jet injection geometries are possible.

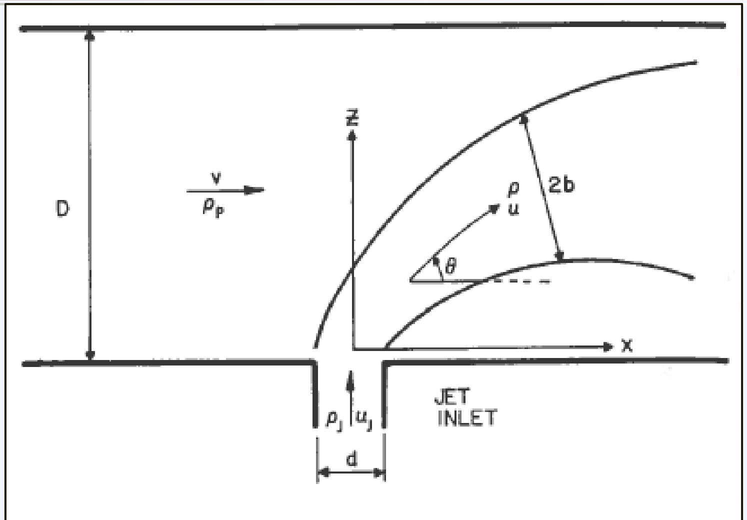


Figure 1. Schematic of a single jet mixer.

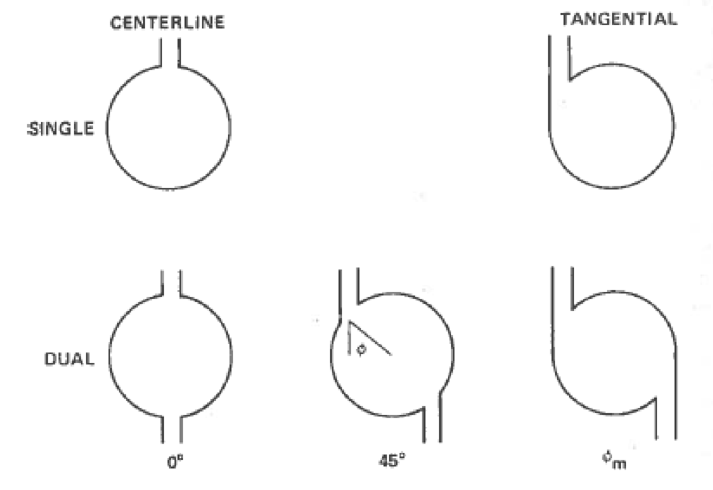


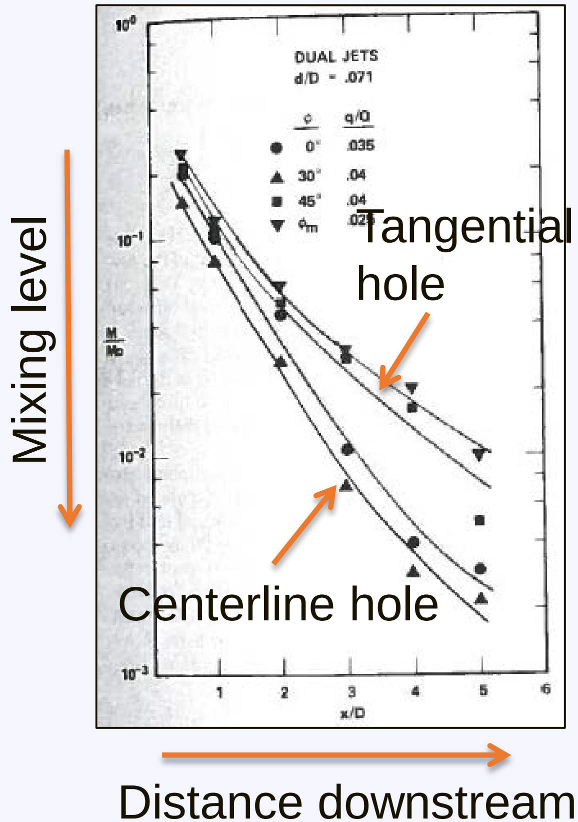
Figure 2. Schematic of single and dual jet mixers.

"Jet Injection for optimum pipeline mixing," Encylcopedia of Fluid Mechanics, vol. 2, Ch. 25, Gulf Publishing, 1986

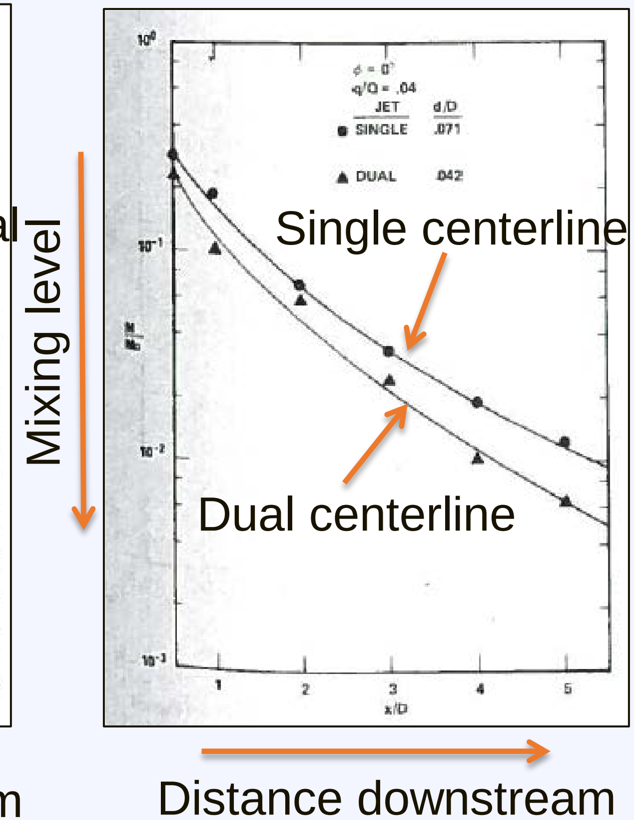
Micromix Combustor Design: Mixing

- Centerline configuration preferred
  - More effective than tangential injection
  - Minimizes fuel addition to the boundary layer
- Single hole configuration preferred
  - Dual hole is more complex and results in smaller feature sizes, but is only marginally more effective.

Tangential vs. Centerline Injection



Dual vs. Single Injection



Single centerline jet provides efficient mixing with simple geometry.

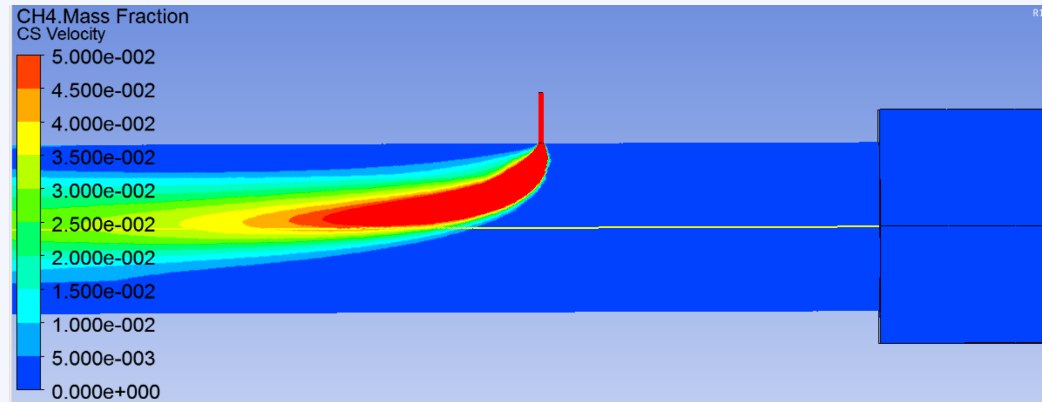
“Jet Injection for optimum pipeline mixing,” Encylcopedia of Fluid Mechanics, vol. 2, Ch. 25, Gulf Publishing, 1986

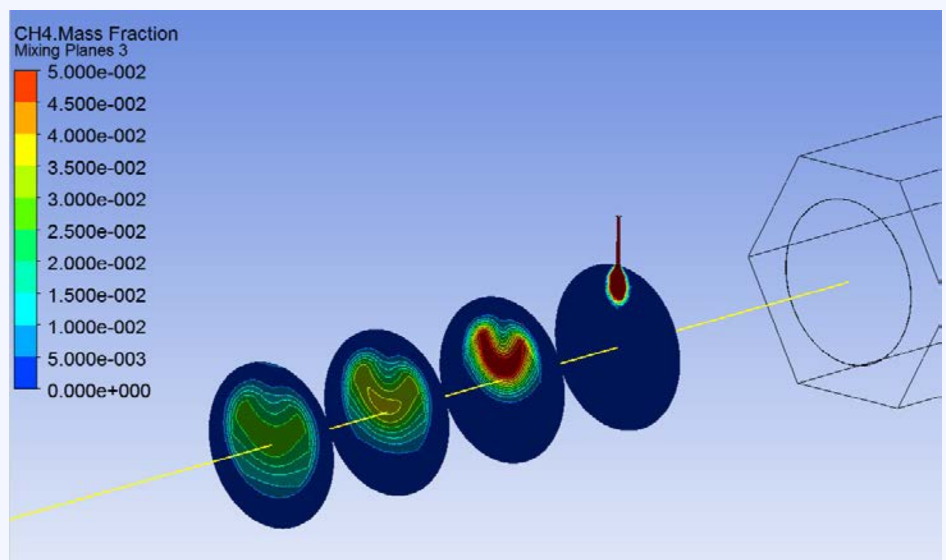
Micromix Combustor: CFD Analysis

- CFD analysis is being performed to trade injector dimensions and emissions.
  - Smaller dimensions result in lower emissions.
  - Larger dimensions are easier to fabricate and more tolerant of contaminants.
- Analysis also used to verify lack of autoignition and flashback.

<u>Example CFD Analysis of an Injector Port</u>

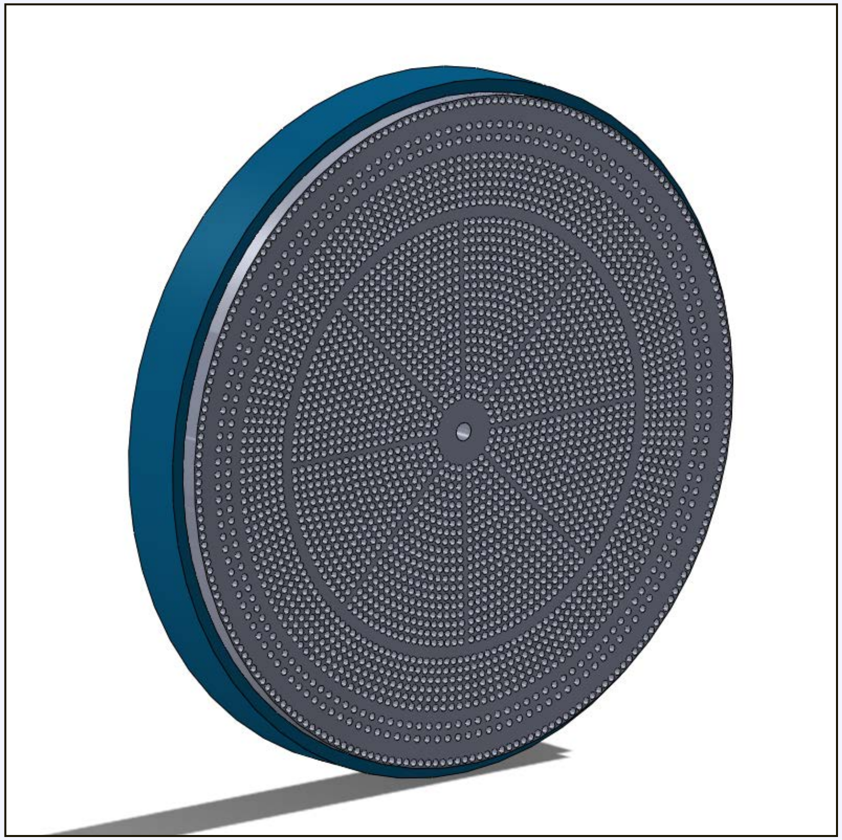
Methane Mass Fractions



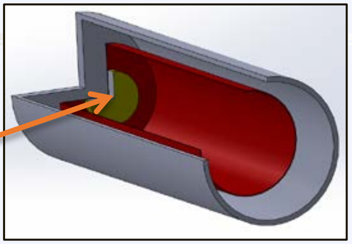


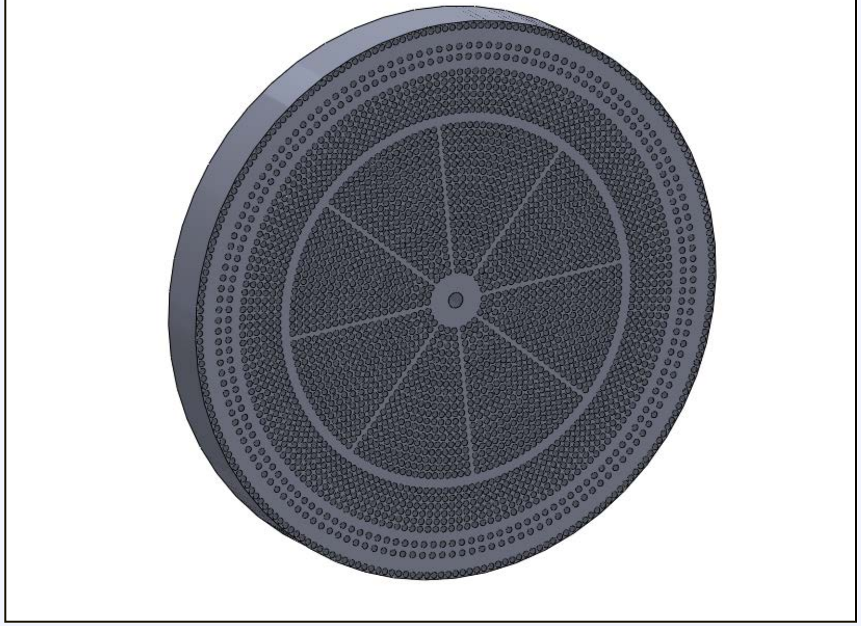
Micromix Combustor: Mechanical Design

Injector Assembly



Injector



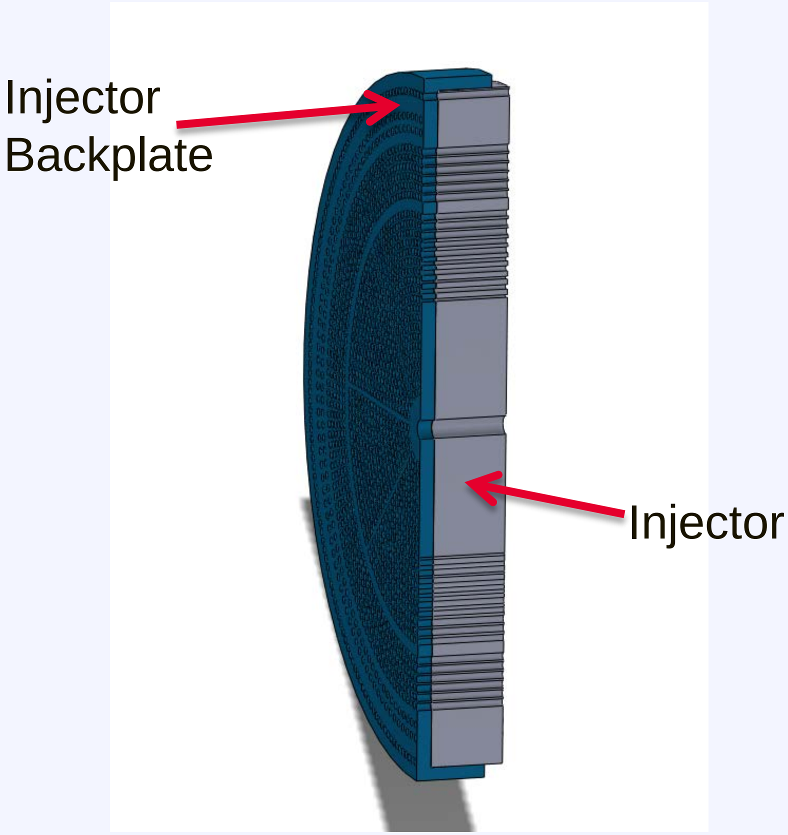


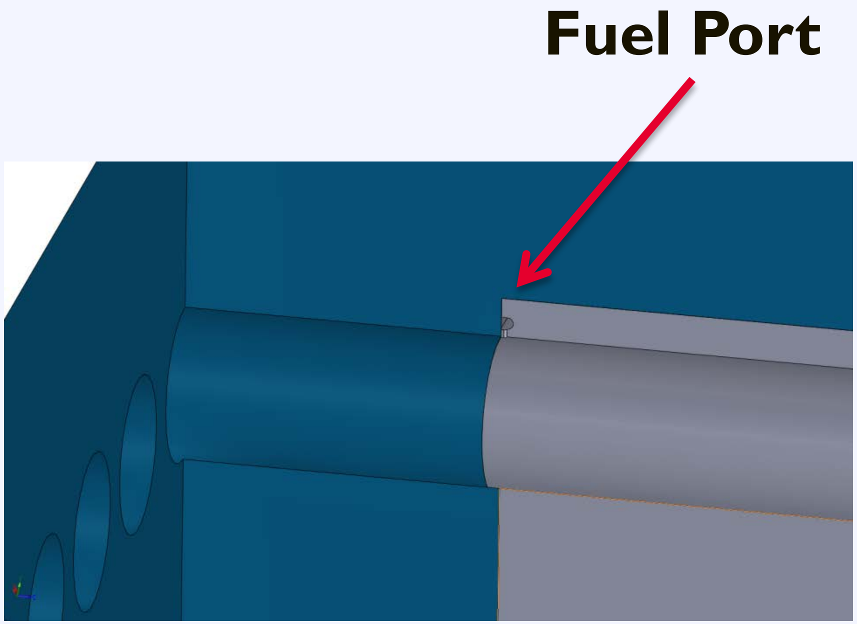
750 holes @ 4 mm

Four tube banks to incrementally handle 600-1,000ºC operation.

Micromix Combustor: Mechanical Design

Assembly Cross-section



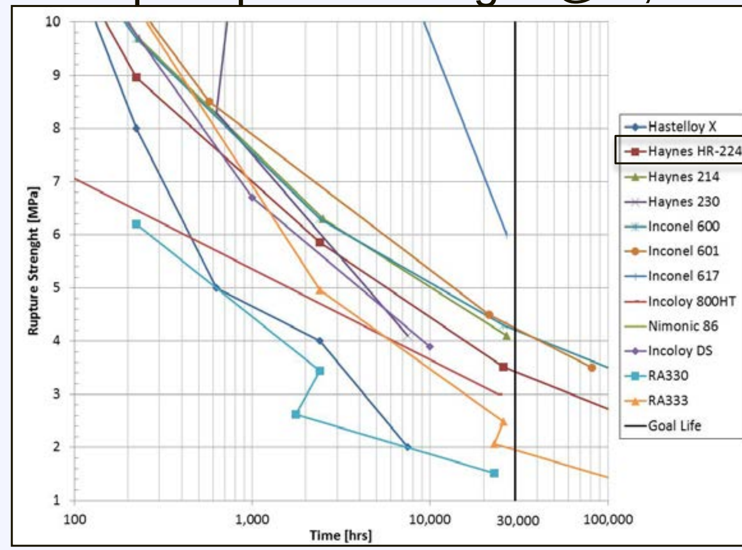


Fuel channels machined on back of main injector plate.

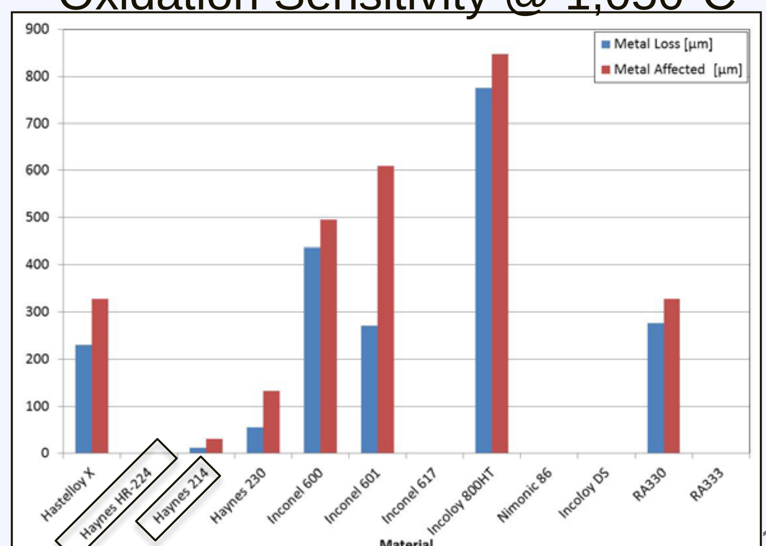
Micromix Combustor: Materials

- Considered 86 materials from Haynes, Special Metals and Rolled Alloys
  - Creep rupture and low cycle fatigue strength
  - Oxidation resistance
    - Particularly important because of high surface area injector.
- Haynes HR-224 provides the necessary capability.
  - New high performance alloy with good formability.
  - Used for both injector and liner.

Creep-Rupture Strength @ 1,050ºC



Oxidation Sensitivity @ 1,050ºC



Micromix Combustor: Materials

- Industry standard: Yttria stabilized zirconia with a MCrAlY bond coat (BC).
  - Applied to inside liner surface and injector face.
- Bond coat applied to all high temperature surfaces to prevent oxidation.
- Experimental low conductivity thermal barrier coatings are also being considered.

Current and Future Work

Active Analyses and Trade Studies

Fabrication and oxidation protection ⟷ Emissions

CFD and Chemical Analysis

Mechanical strength and simplicity ⟷ Thermal stress and temperature limitations

Structural and Heat Transfer Analysis

Other Design Efforts

- Test rig design is underway with significant contributions from Solar Turbines (proprietary).
- Evaluation of micromix injector fabrication techniques.

Future Work

- Acoustic analysis and fuel control system design.
- Detailed drawings to prepare for Phase II.