# Direct Fired Oxy-Fuel Combustor for sCO2 Power Cycles


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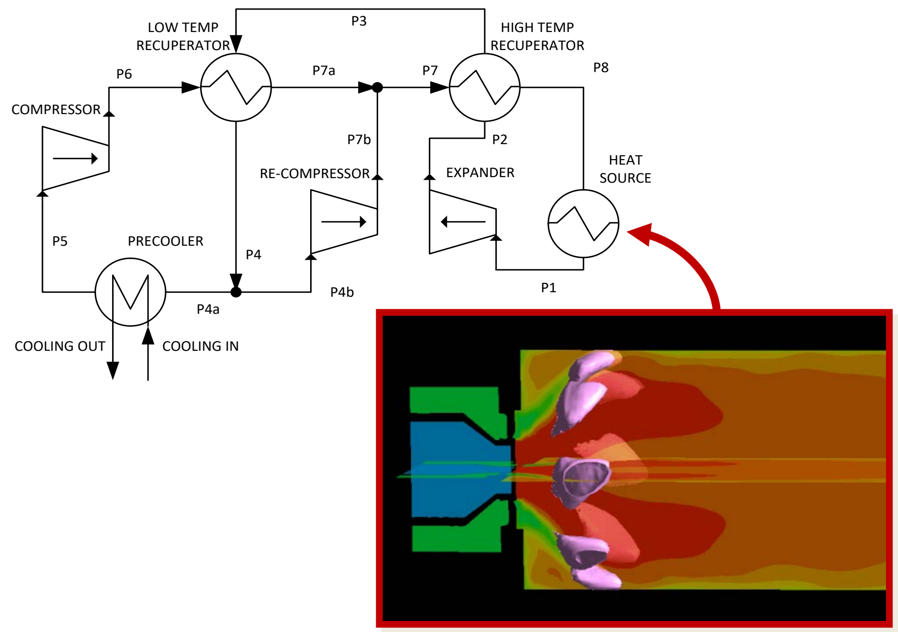
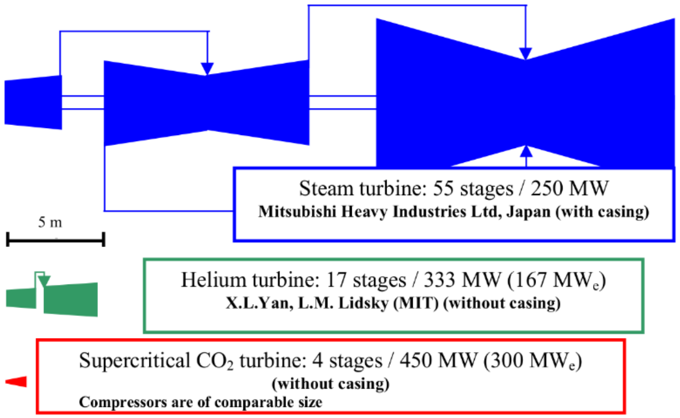


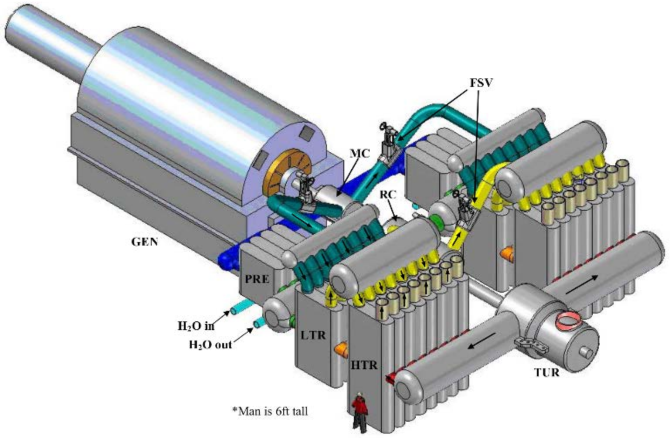
# Outline

- Background
- Project Objectives
- Data From Bench Top Test
- Combustor Design
- Test Loop Design
- Future Work

# Why sCO2 Power Cycles?

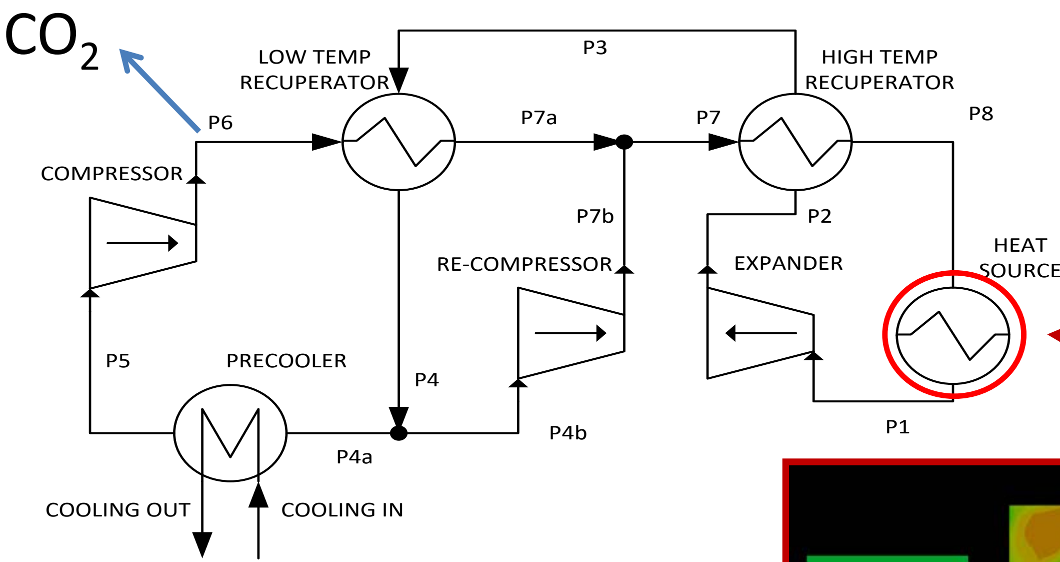
- Offer +3 to +5 percentage points over supercritical steam for indirect coal fired applications
- High fluid densities lead to compact turbomachinery
- Efficient cycles require significant recuperation

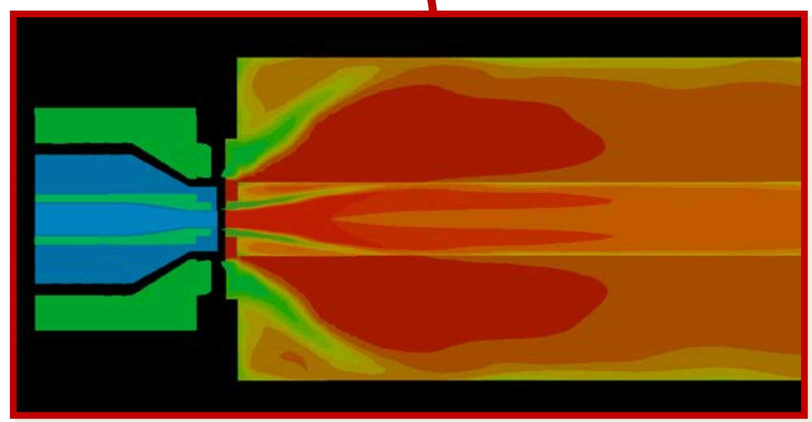



Third Generation 300 MWe S-CO2 Layout from Gibba, Hejzlar, and Driscoll, MIT-GFR-037, 2006

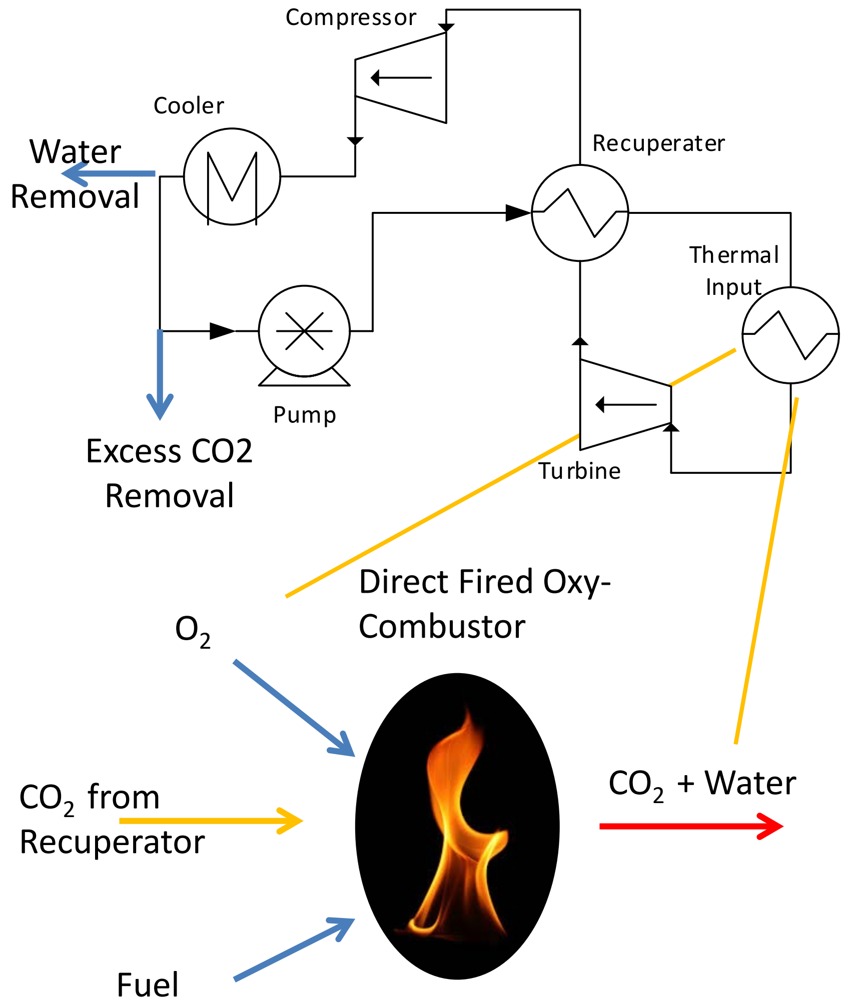
# Why Oxy-Fuel Combustion?



- Capture 99% of carbon dioxide
- Higher turbine inlet temperatures possible

# Oxy-Combustion




- Oxygen + fuel
- Direct fired sCO2 combustors have a third inert stream
- Challenge:
  - Mix and combust fuel without damaging the combustor

# Project Objectives

- Design a 1 MW thermal oxy-fuel combustor capable of generating 1200°C outlet temperature
- Manufacture combustor, assemble test loop, and commission oxy-fuel combustor
- Evaluate and characterize combustor performance
  - Optical access for advanced diagnostics

# Project Schedule

- Design Phase: 31 Dec 2017
  – Combustor design
  – Loop design
- Manufacturing construction and commissioning: 1 Jan. 2018 – 31 Dec. 2019
- Test and data collection: 1 Jan 2020 – 31 March 2021

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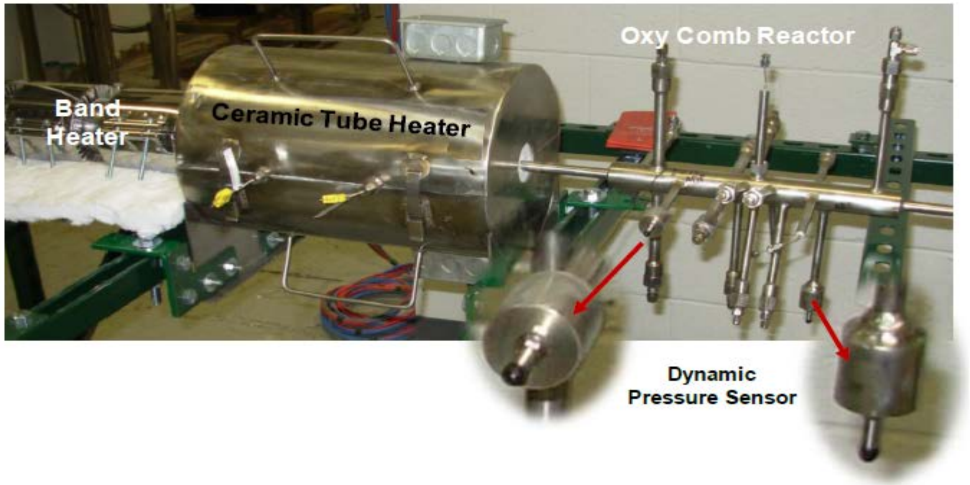
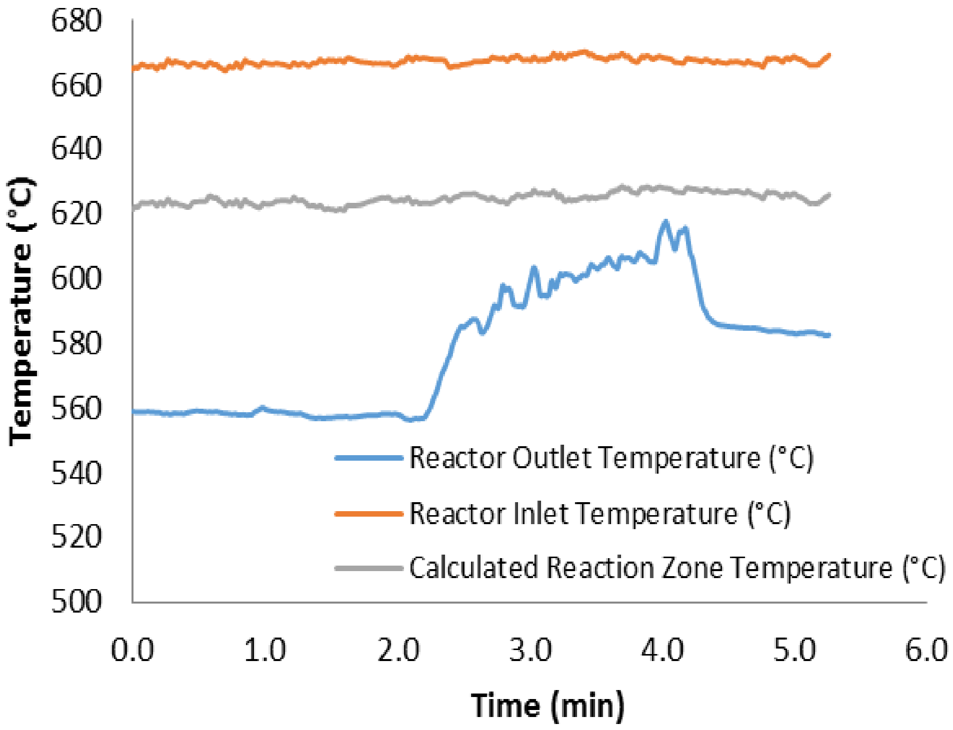
# Bench Top Reactor

- 1/4in diameter
- Continuous flow auto-ignition reactor
- Inlet conditions ~900°C and 200bar



# Bench Top Reactor Temperature Profile

- Significant heat transfer within the reactor
- Auto-ignition occurred at a significantly lower temperature than expected
- Combustion zone temperature calculated based on a constant heat flux assumption
- Combustion zone temperature well below design temperature
  - Sufficient fuel and oxidizer for 1100°C



# Results Discussion

- Fuel and oxidizer were sufficient to raise outlet temperature to ~1100°C
- Why didn't it?
  - Mixing time
  - Chemical kinetics
  - Heat transfer and wall effects
- Auto ignition occurred at high concentrations of CO2 at ~620°C

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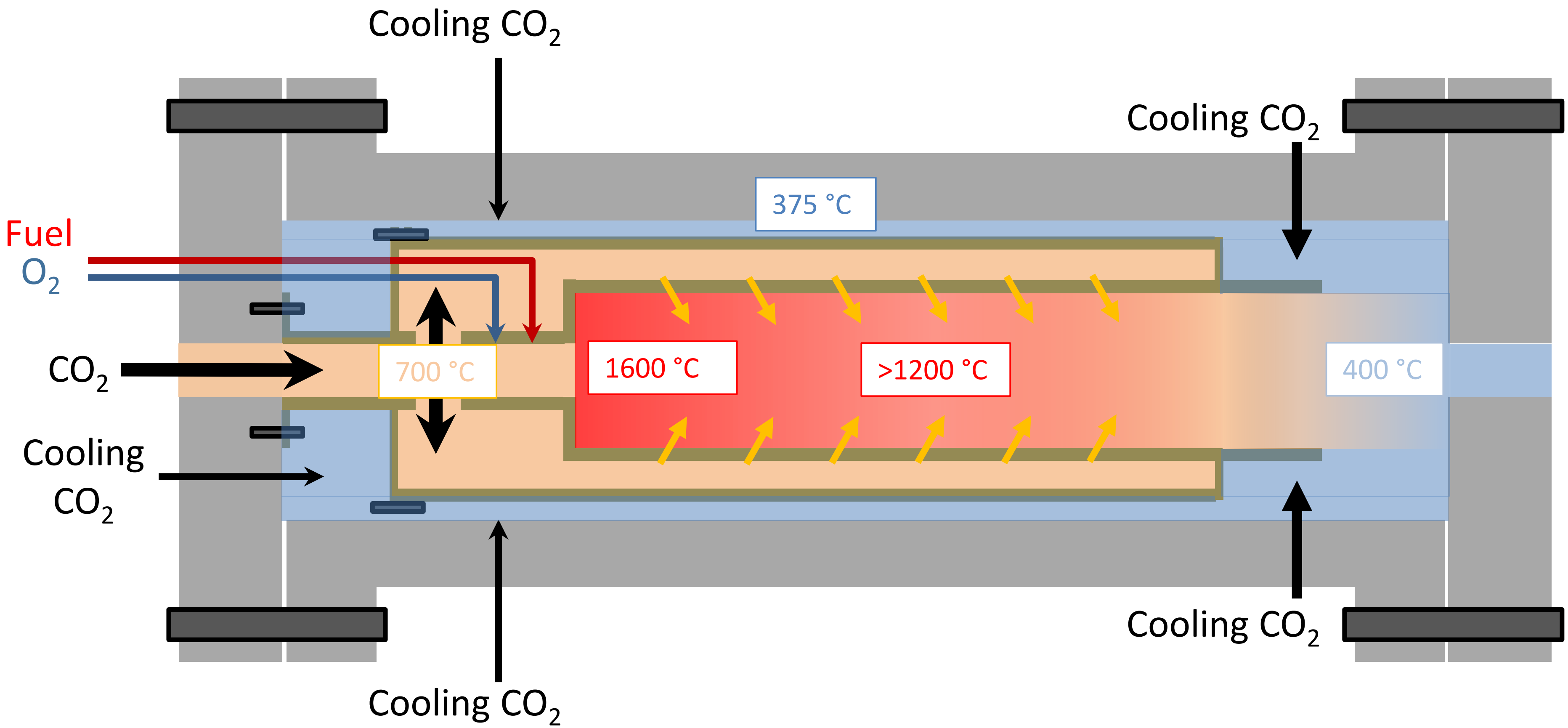
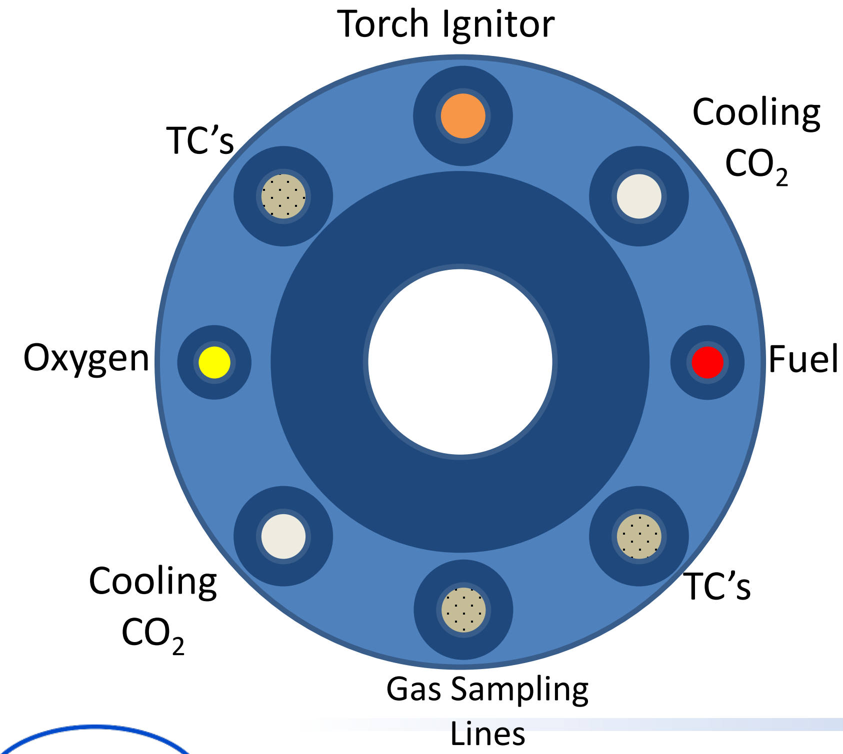
# Combustor Casing Design

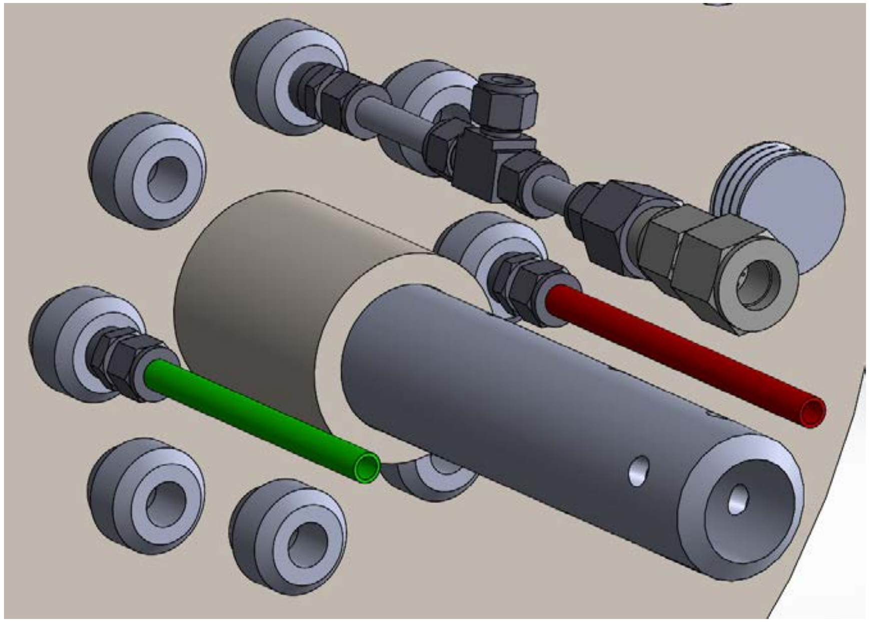



Pressure: 250 bar
Temperature: 375-700 °C

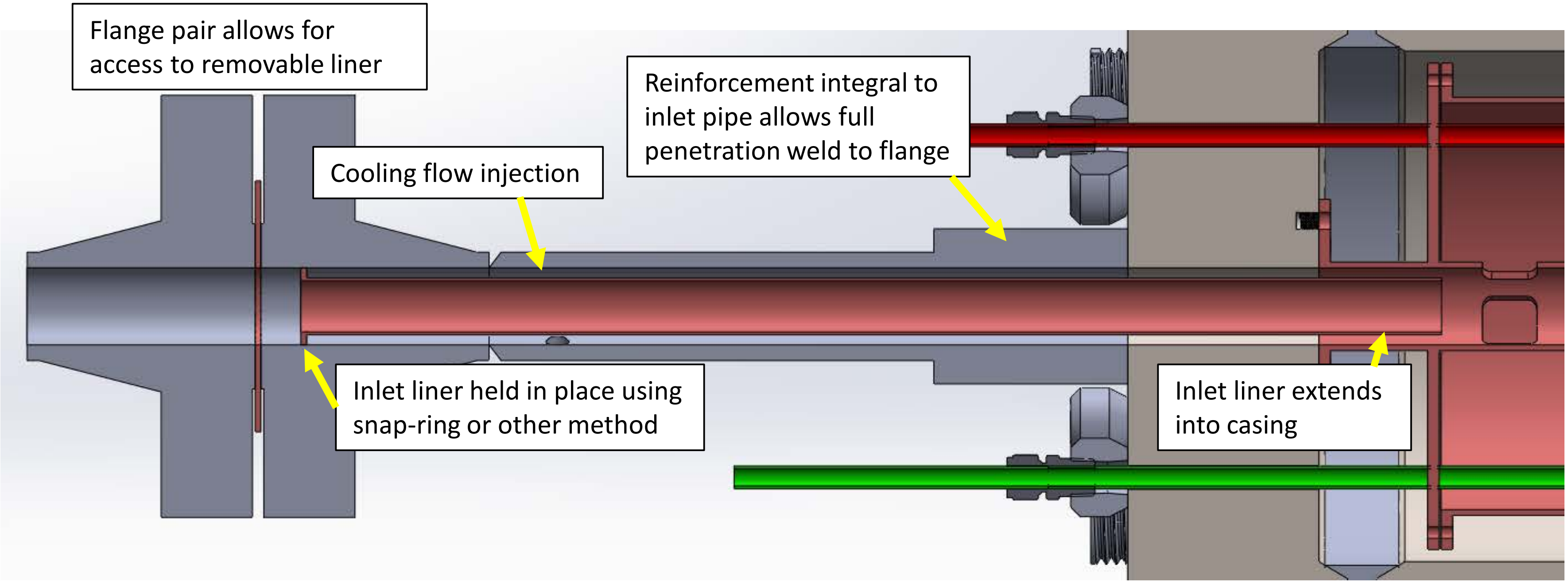
# Reinforcement collar needed for hot $CO_2$ center opening

- Calculated using ASME Section VIII Div. 1, UG-39
- 3.4” OD, 2.375” ID, 4.25” long collar satisfies conditions and minimizes interference with other lines



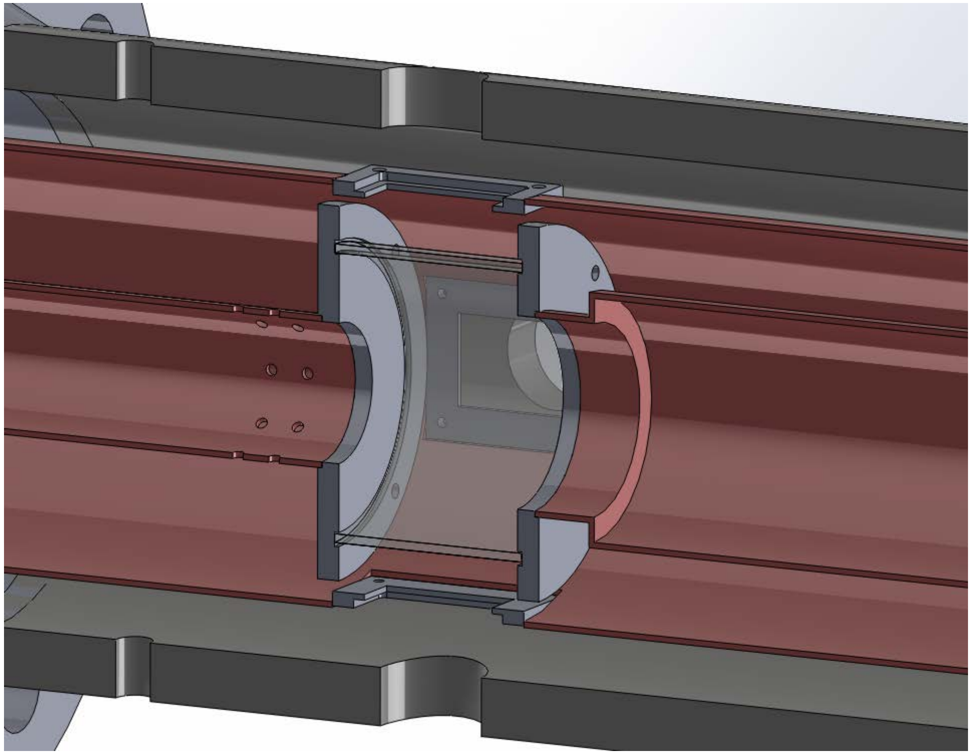



# Inlet pipe will use a cooled-jacket liner to keep flange temperatures lower

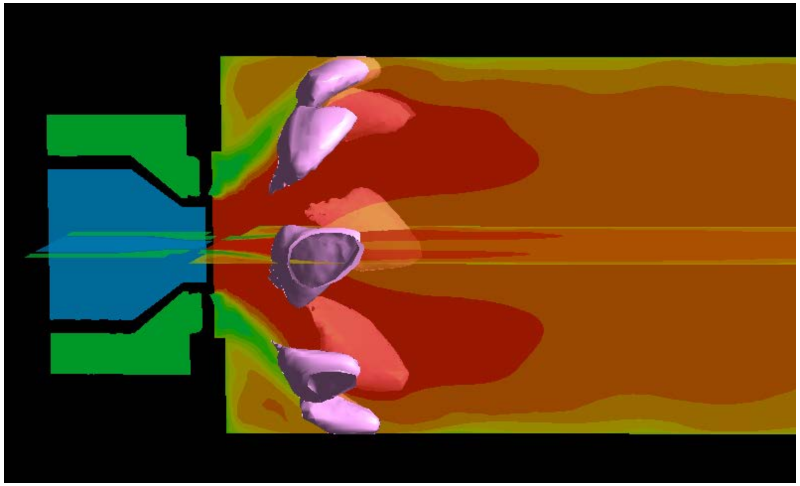


# Optical window concept uses three layers of windows to peer into combustion chamber

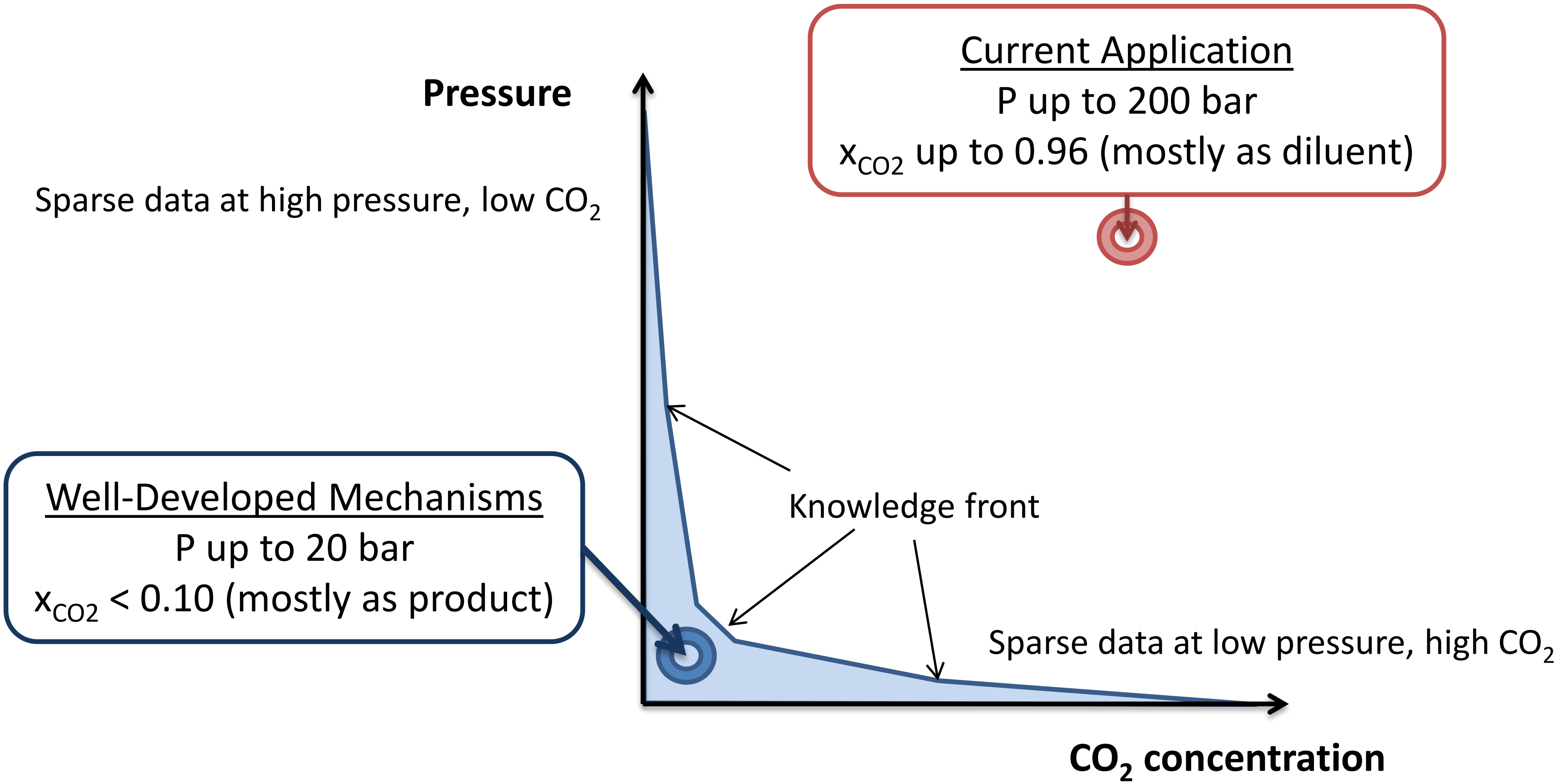
- Laser ignition
- Trouble shoot combustor operation
- Optical access for simple visible light diagnostics



# Combustor Aero-Thermal Design



# Kinetics Knowledge Base




**No data available at conditions relevant to this application.**

# Mechanisms are compared in a isobaric zero-dimensional reactor

Temperature vs. time results are presented for a range of temperatures and pressures

| | 554 °C | 654 °C | 754 °C | 854 °C | 954 °C |
|---|---|---|---|---|---|
| **100 bar** | | | X | | |
| **200 bar** | X | X | X* | X | X |
| **300 bar** | | | X | | |

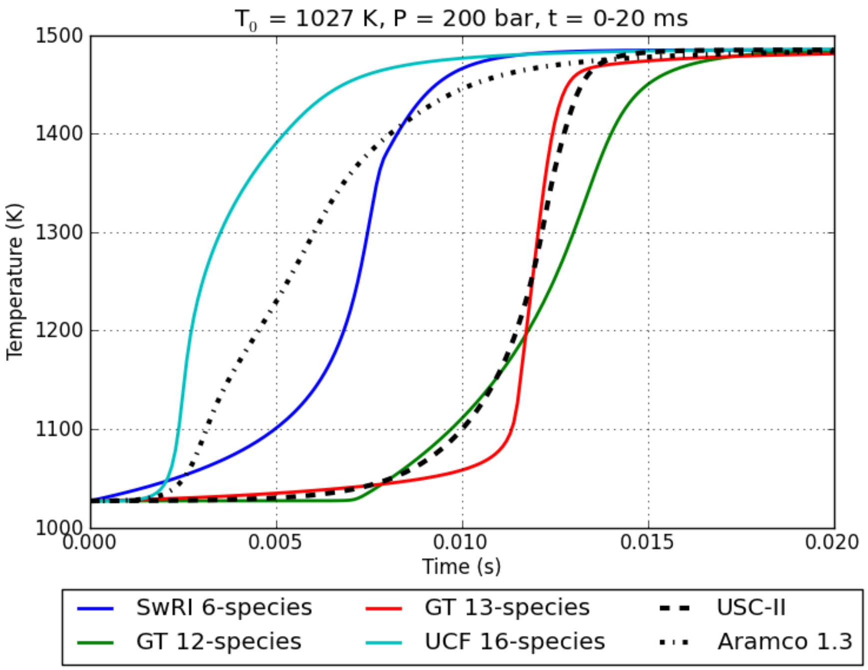
* - High and low equivalence ratios also evaluated for this point

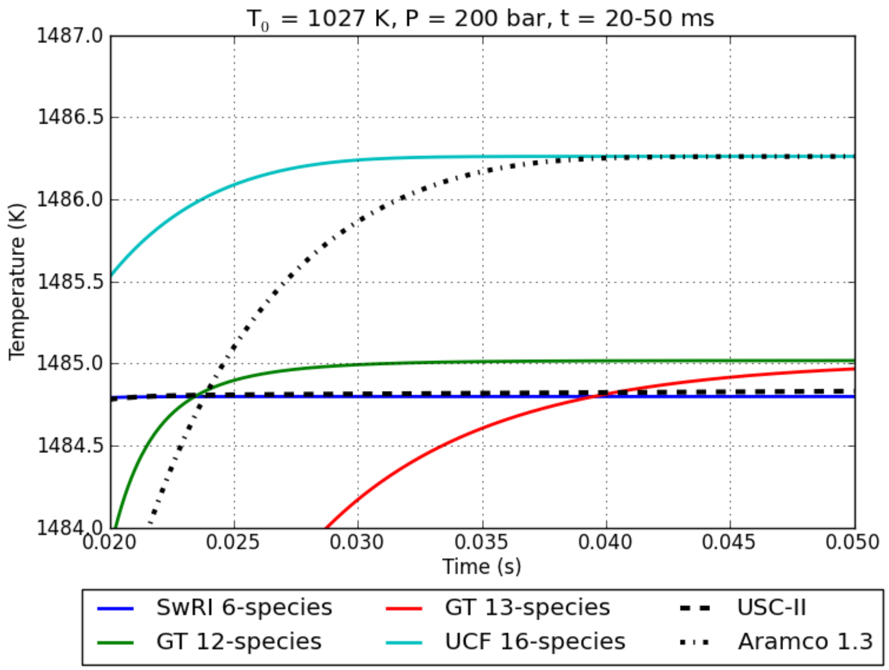
Nominal starting composition for each case (mole fractions)

| Mechanism | $CO_2$ | $O_2$ | $CH_4$ | $C_2H_6$ |
|---|---|---|---|---|
| **Aramco 1.3, USC-II, Georgia Tech, and UCF** | 0.902 | 0.066 | 0.032 | - |
| **SwRI 6-species** | 0.903 | 0.066 | 0.029 | 0.0015 |

- SwRI 6-species fuel quantity adjusted to match the adiabatic flame temperature of the USC-II case (that used pure methane)

# T = 754°C, P = 200 bar, ϕ = 1.0



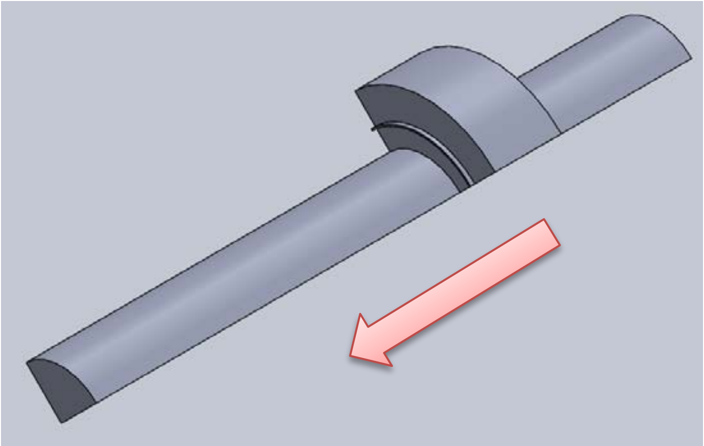



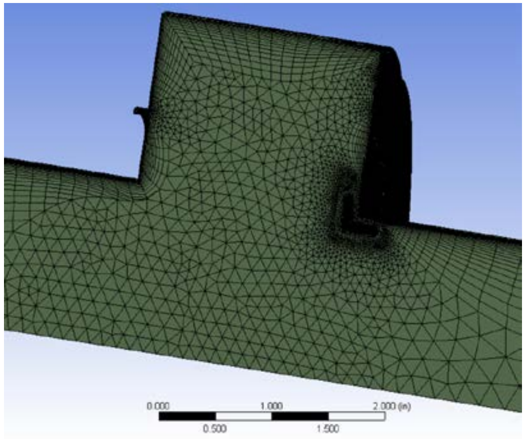
# Computational Design

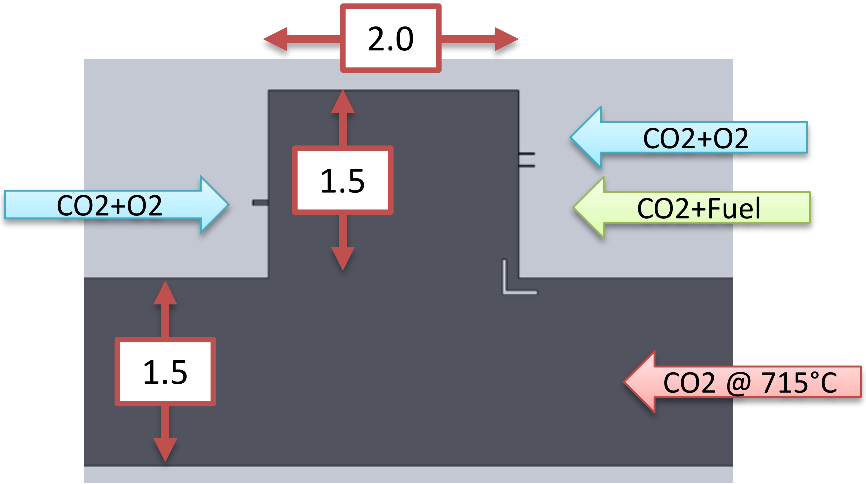
- Early design efforts constrained by high inlet temperatures needed to operate in a recompression  cycle ~900°C combustor inlet
- Recuperator technology unlikely to be able to support those temperature in the near future
- Lower inlet temperature allow for easier design of submerged aerodynamic components

# New Explored Concept: Trapped vortex CFD setup

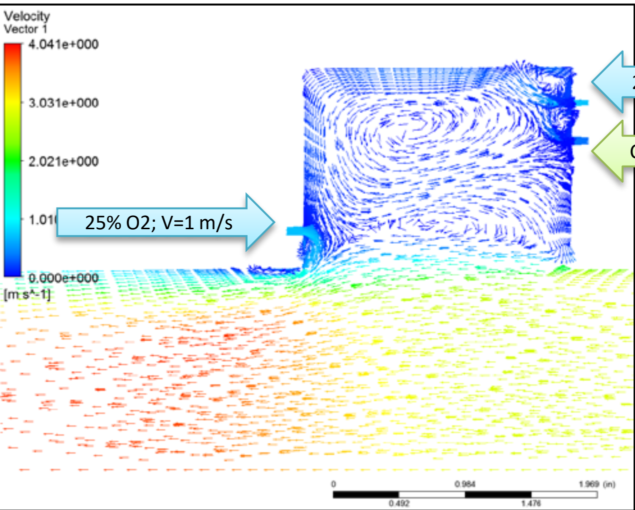
- ¼ Symmetry
- Mesh refinement near walls & injectors
- 18” total length with 5” inlet pipe
- Cavity injection at 20°C
- Fuel/$CO_2$ mass fraction ratio was 25%/75% for all simulations
- $O_2$/$CO_2$ inlet streams were varied and are noted on results pages.
- Simulations were run with cold flow (reactions not activated) and with reactions activated

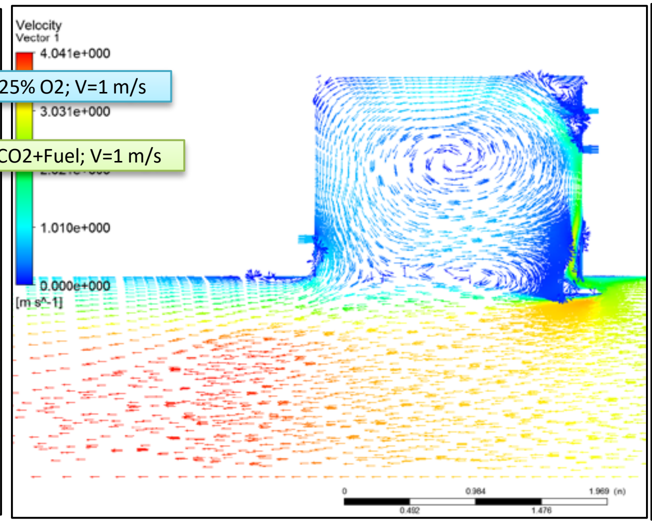


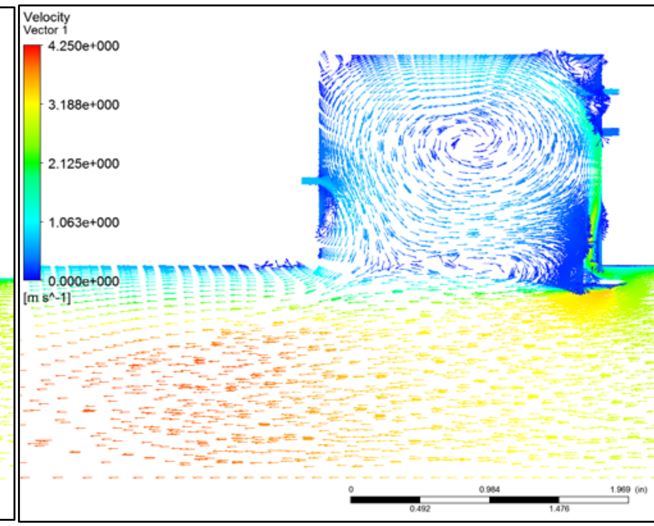




# Trapped vortex combustor simulations: Sim ID: 501-502, 504 Cold Aft Injection



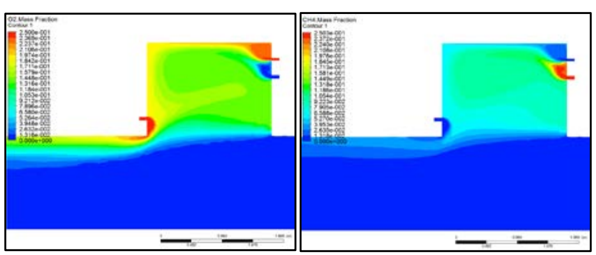



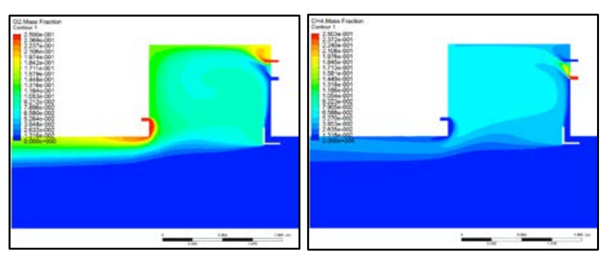



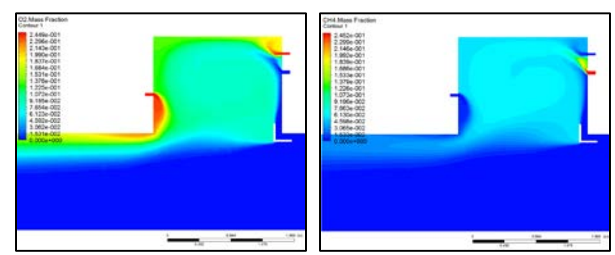

501: No Deflector

502: Deflector

504: Deflector



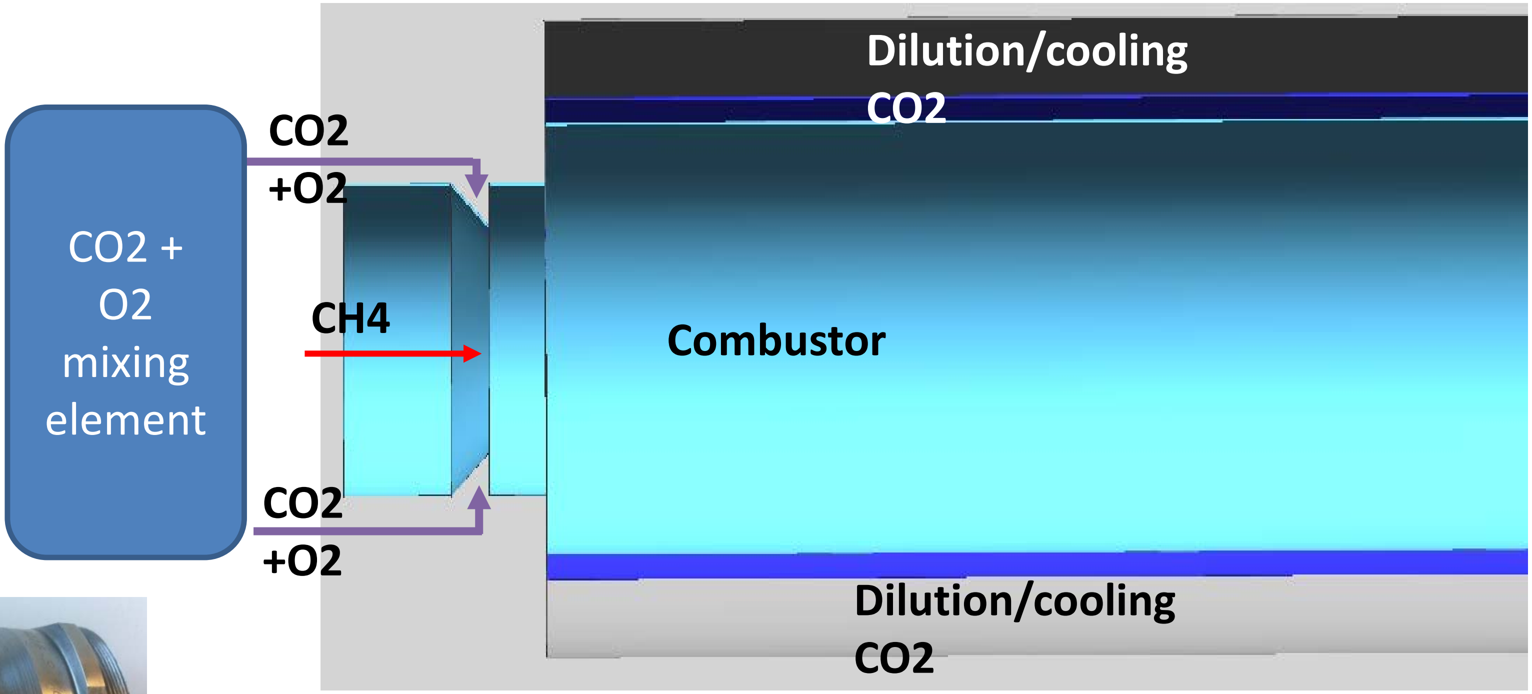




# TVC Conclusion

- The study performed agreed with the risks discussed in the literature, in addition to the unknown risks of sCO2, specifically:
  - Combustor performance is sensitive to injector location and injector velocity
  - Mechanical deflector/mixer required to enhance mixing between cavity and main flow
  - Cooling walls and window visibility would also be another source of risk.
- The amount of risk has led to a halt in exploring this technology. A more conventional design is now being explored

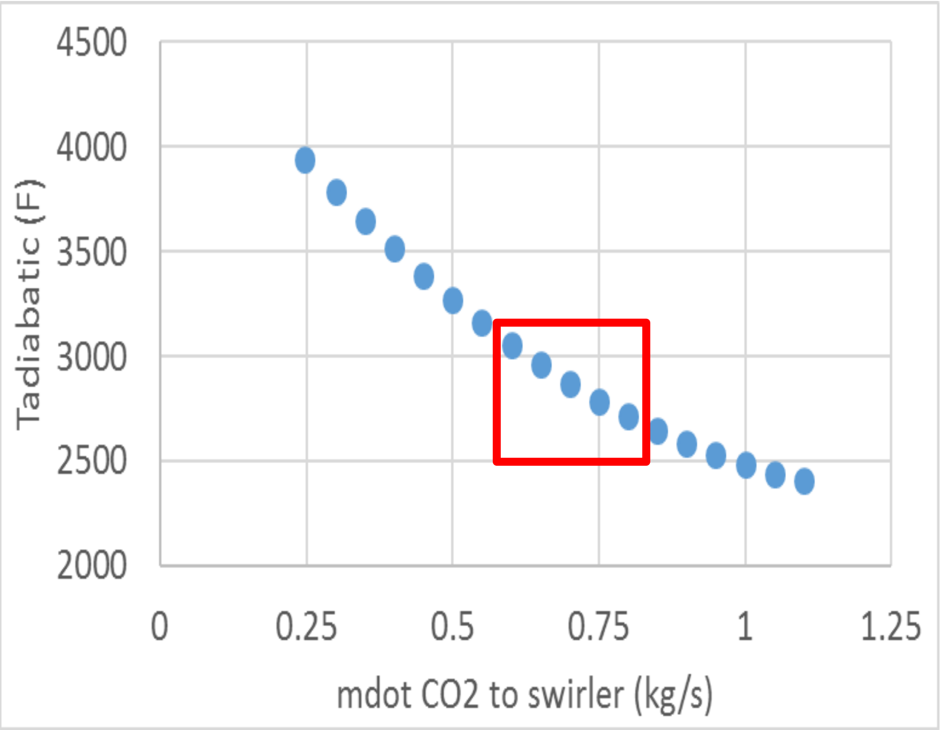
# Schematic of Combustor Design Concept




- Basis: DLN-1 primary fuel nozzle
- Wide operability, stable flame, and extensive experience with this design

# Range of CO2 Flow Splits to Primary Combustor & Bypass Cooling

| Component | Mass Flow (kg/s) |
|---|---|
| CH4 | 0.02 |
| O2 | 0.08 |
| CO2 to combustor | 0.6 - 0.8 |
| CO2 to bypass | 0.925 – 0.725 |
| Total mass flow | 1.625 |



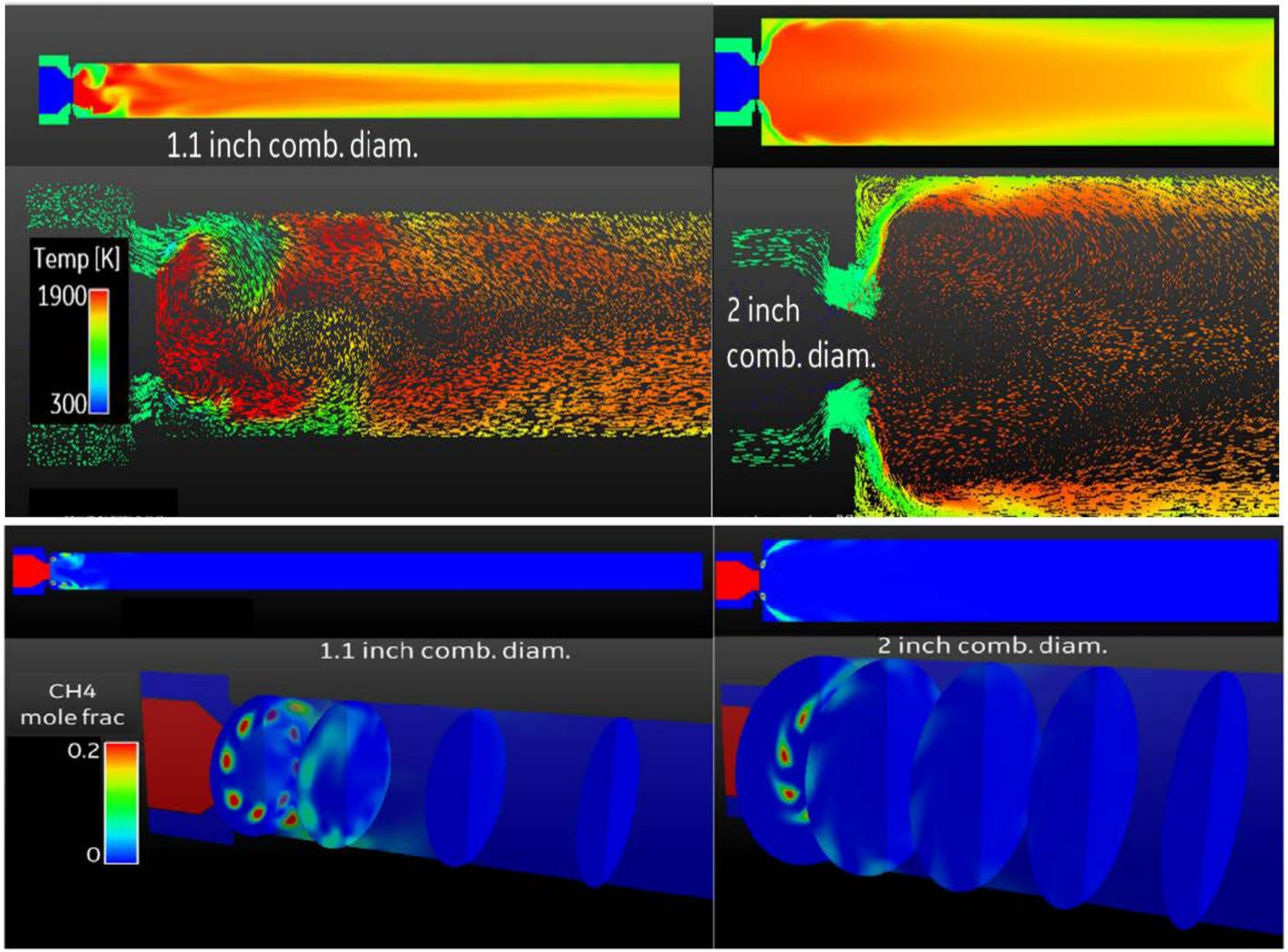

Aiming for $T_{adiabatic}$ = 2700-3000 F for flame stability

# Combustor Design Point

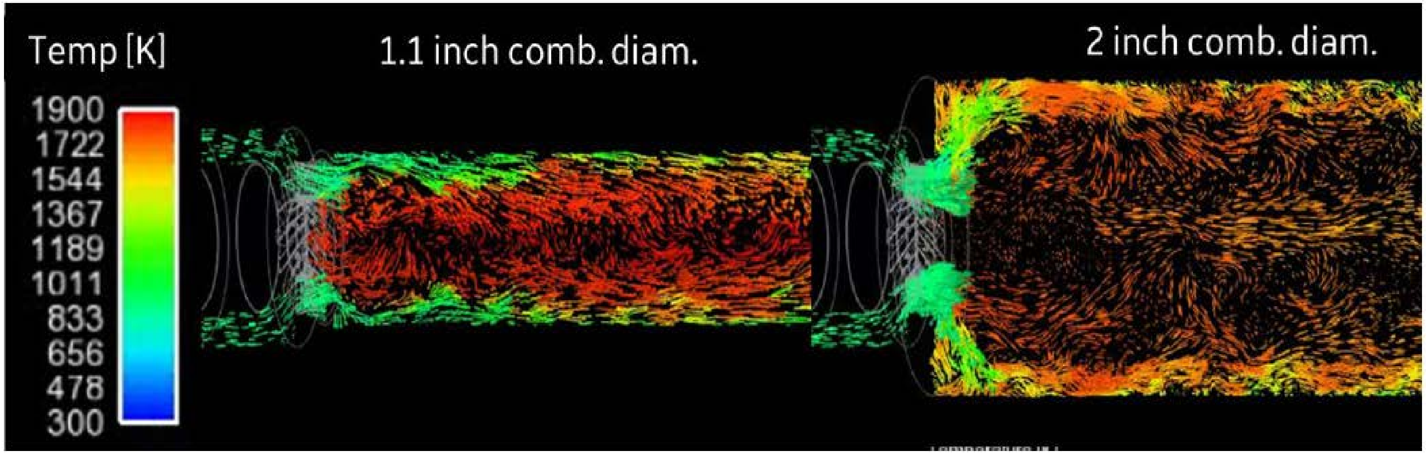
| Component | Mass Flow (kg/s) |
|---|---|
| CH4 | 0.02 |
| O2 | 0.08 |
| CO2 to combustor | 0.626 |
| CO2 to bypass | 0.899 |
| Total mass flow | 1.625 |

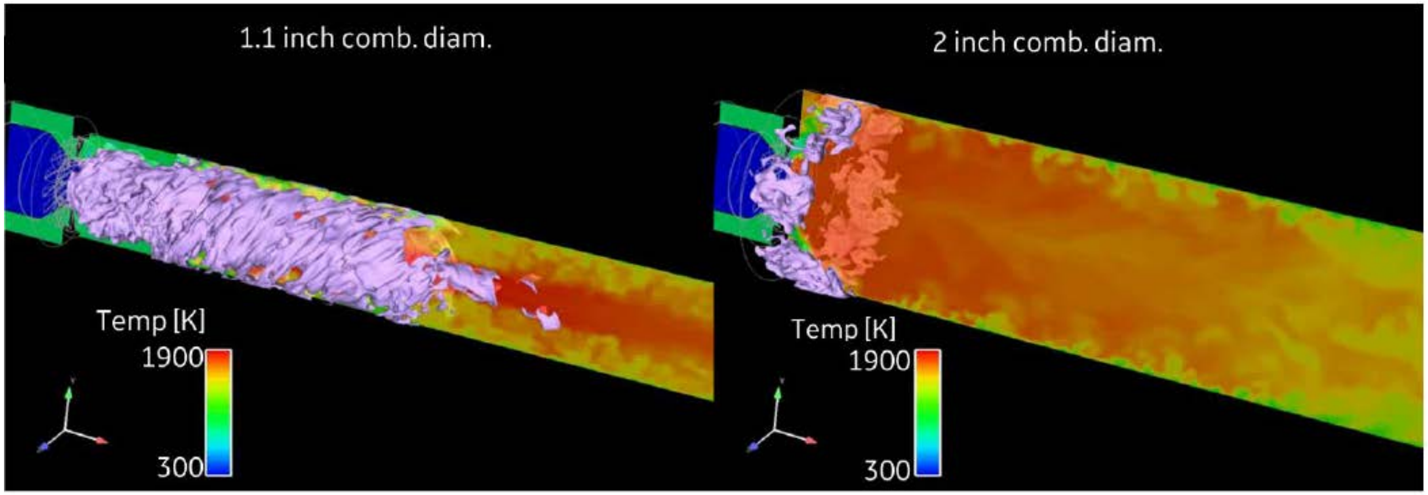
- Design point for adiabatic flame temperature of 3000 F
- CO2 flow distributed as diluent or as bypass as shown above
- GE in-house spreadsheet tools used to determine effective area and combustor size

# GE RANS Simulations



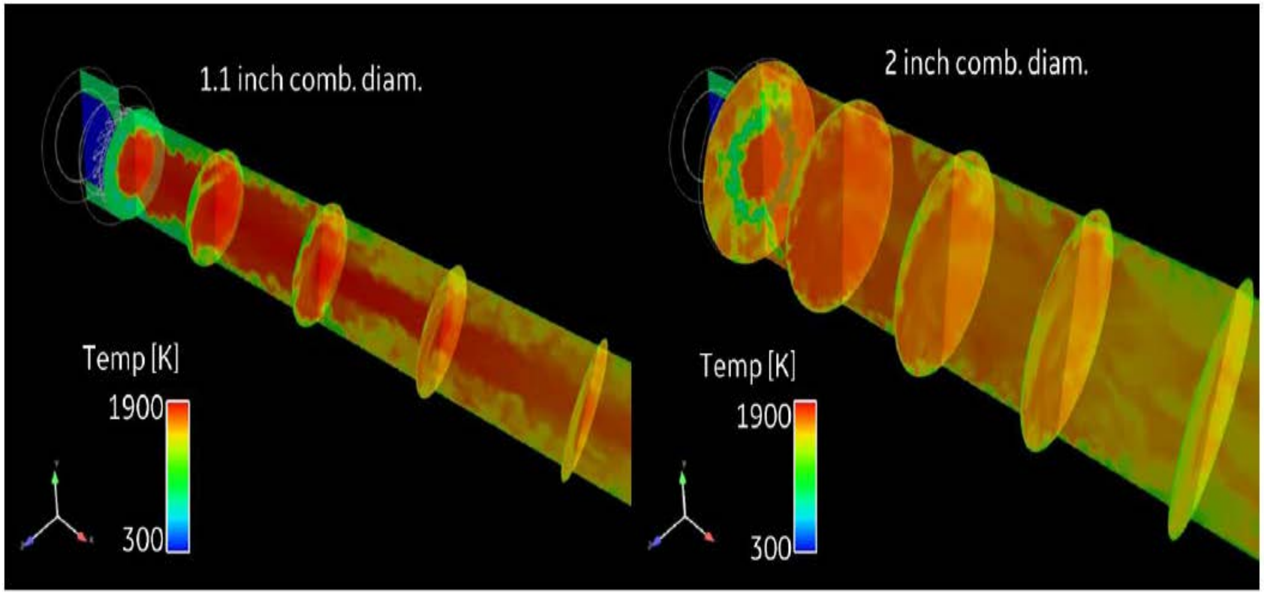
# GE LES Simulations



# GE Results

- 2in diameter combustor performed significantly better than 1.1in diameter
- Further variations in combustor sizing/residence time to be considered

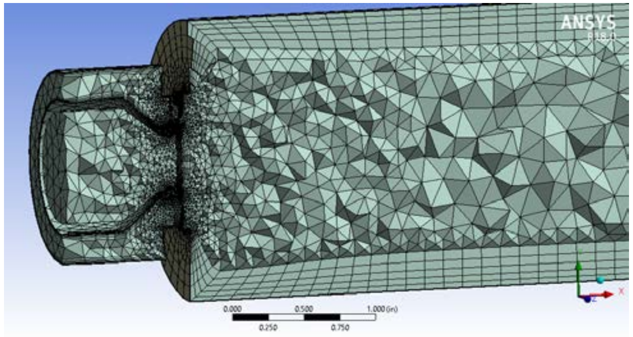


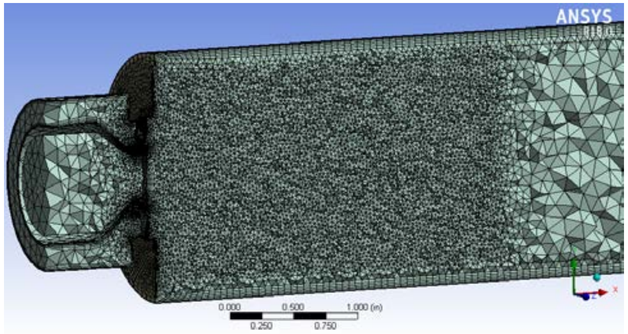
# SwRI RANS Simulations

- Many simulation runs
- Four different cases reported here

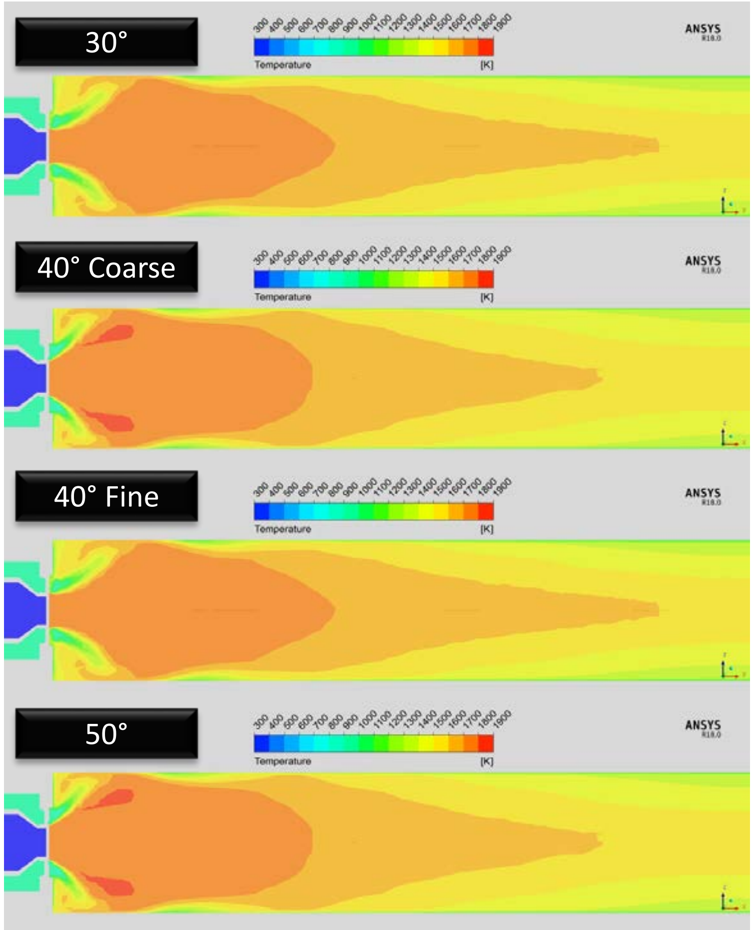
| Simulation Name | Swirl Angle | Mesh Elements |
|---|---|---|
| Variation 30 | 30° | 614,909 |
| Variation 40C | 40° | 628,966 |
| Variation 40F | 40° | 2,126,683 |
| Variation 50 | 50° | 657,858 |

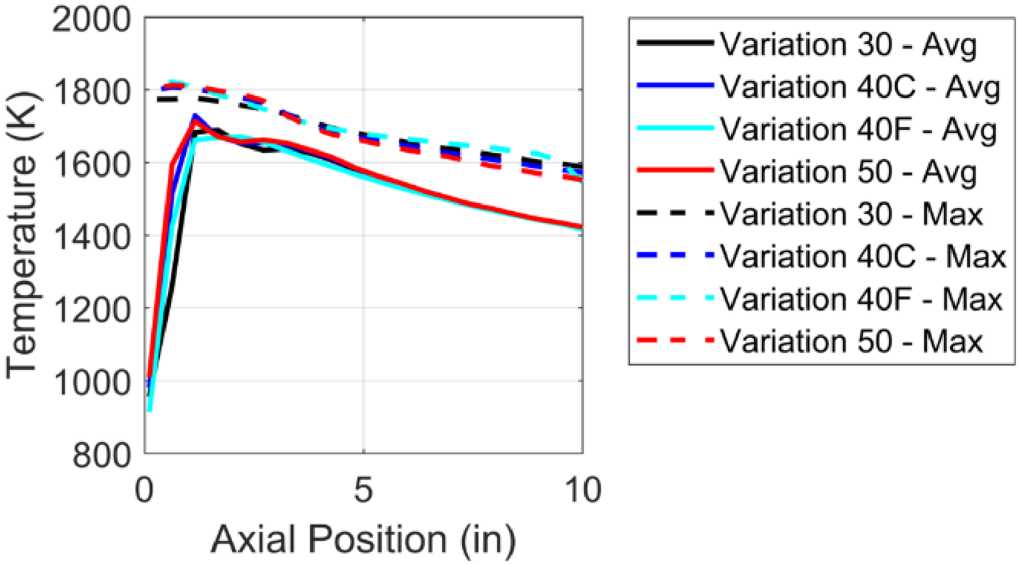
CFD Modeling Setup
- Pseudo Steady State RANS
- Realizable $k$-$\epsilon$ model
    - Standard wall function
- Compressibility
- Pressure outlet
- Mass flow inlet
- Effusion cooling mass sources



# Temperature Predictions



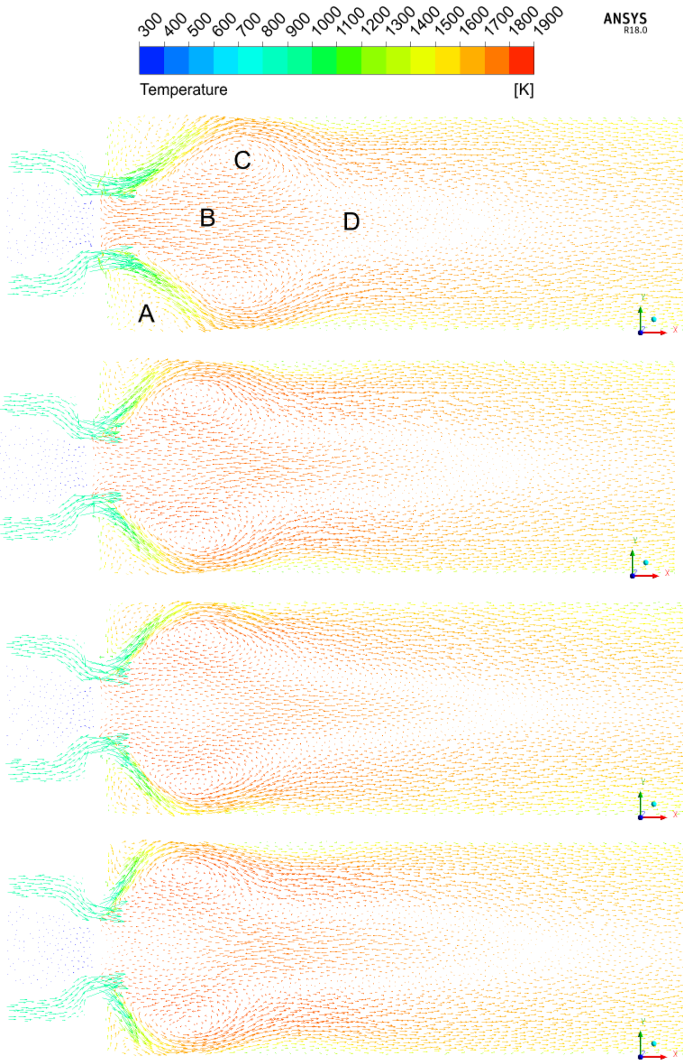
# Flow Predictions

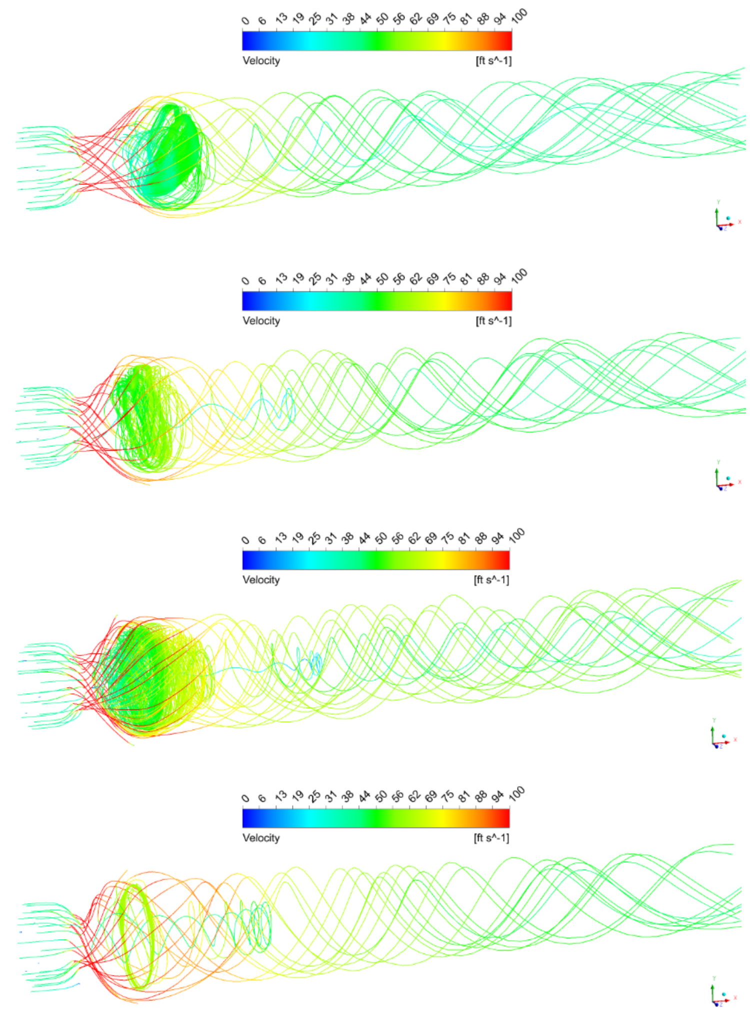
30°

40° Coarse

40° Fine

50°



# CO Concentrations

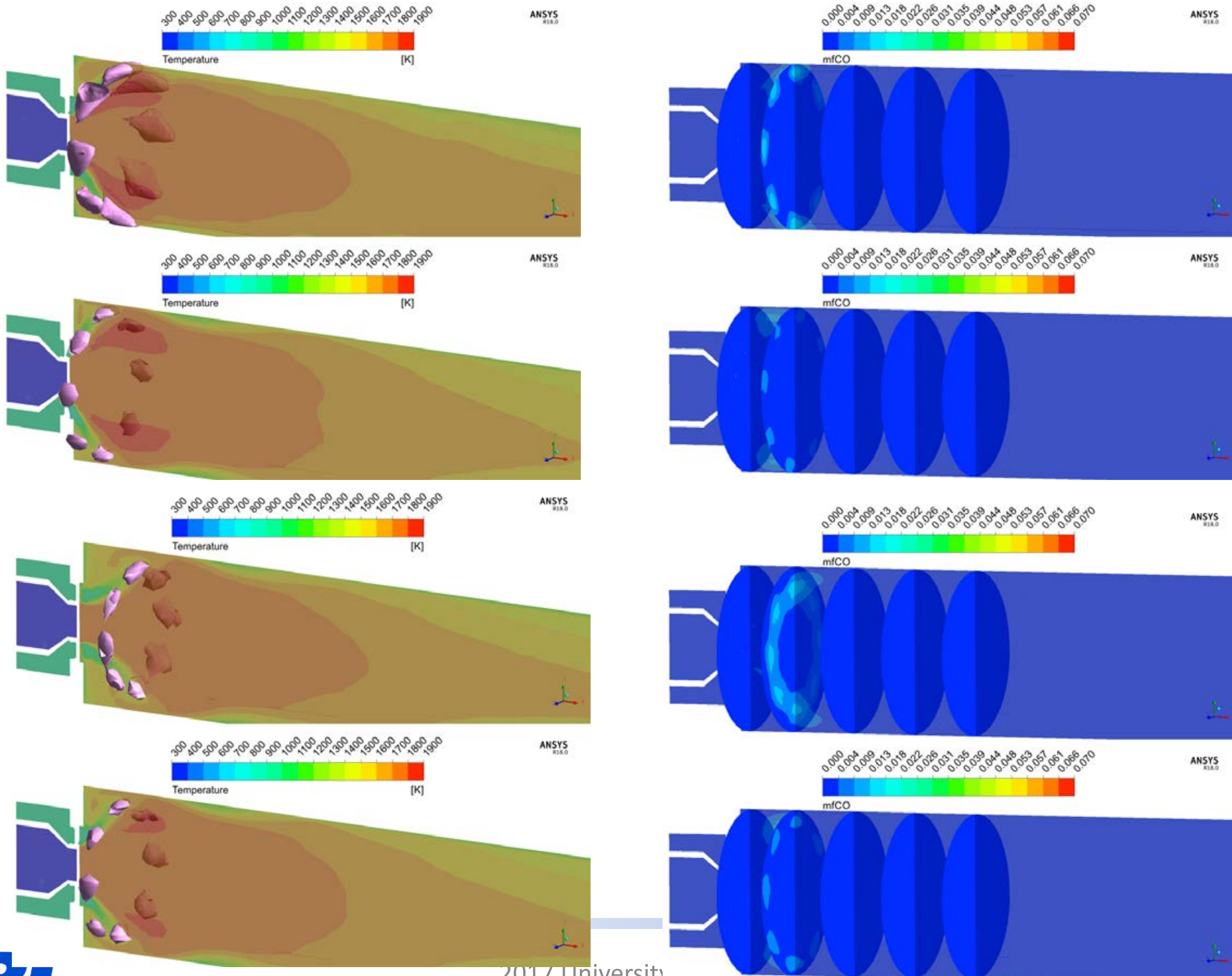
30°

40° Coarse

Light Purple zones are for mole fraction CO=0.008

40° Fine

50°



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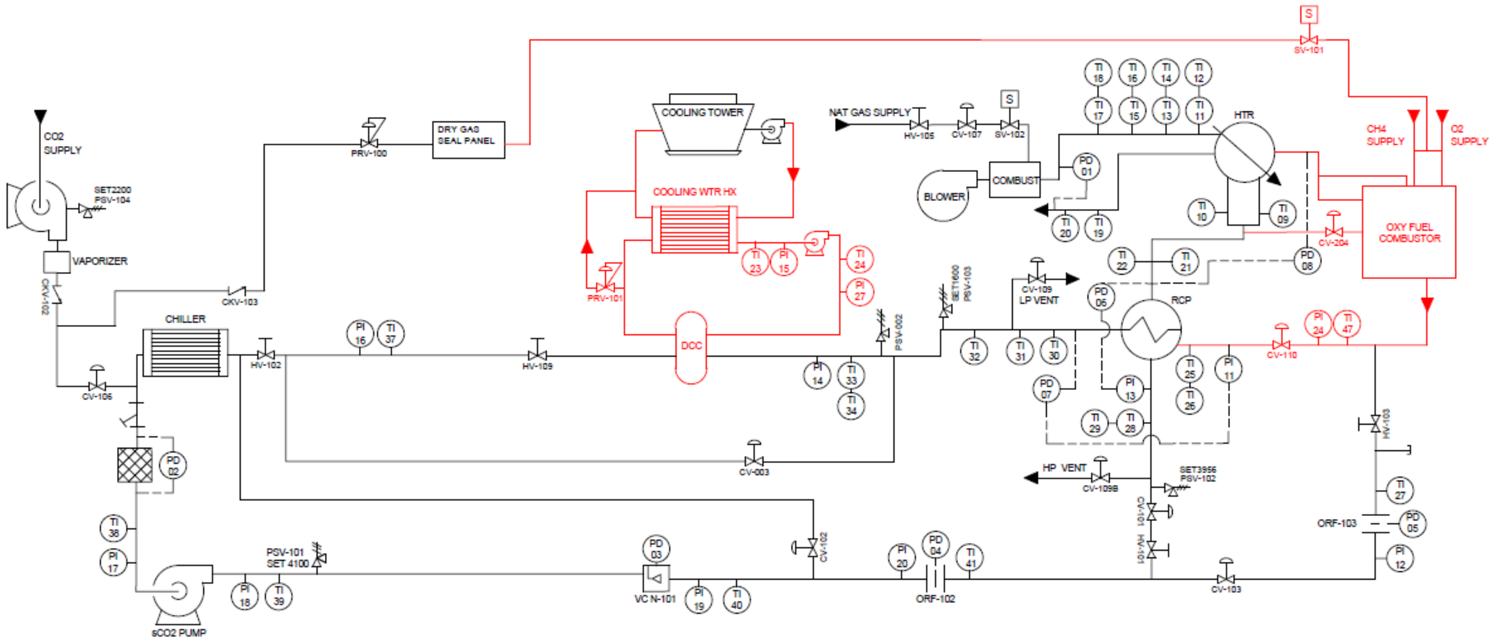
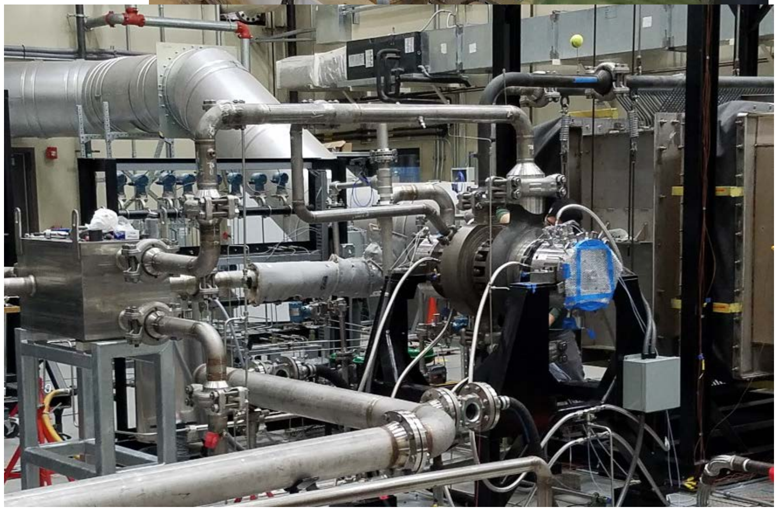
# Combustion Loop P&ID



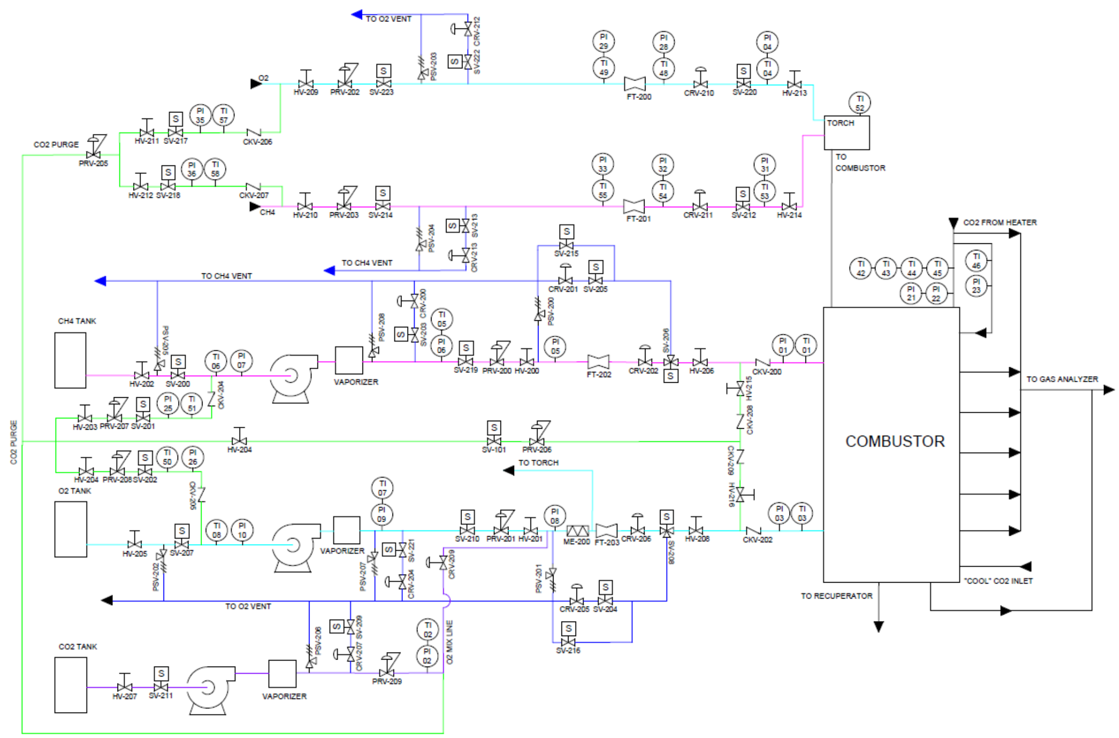
# Sunshot Test Loop

- The project will use the "Sunshot" loop currently being commissioned at SwRI
- Sunshot turbine will be replaced with letdown valve



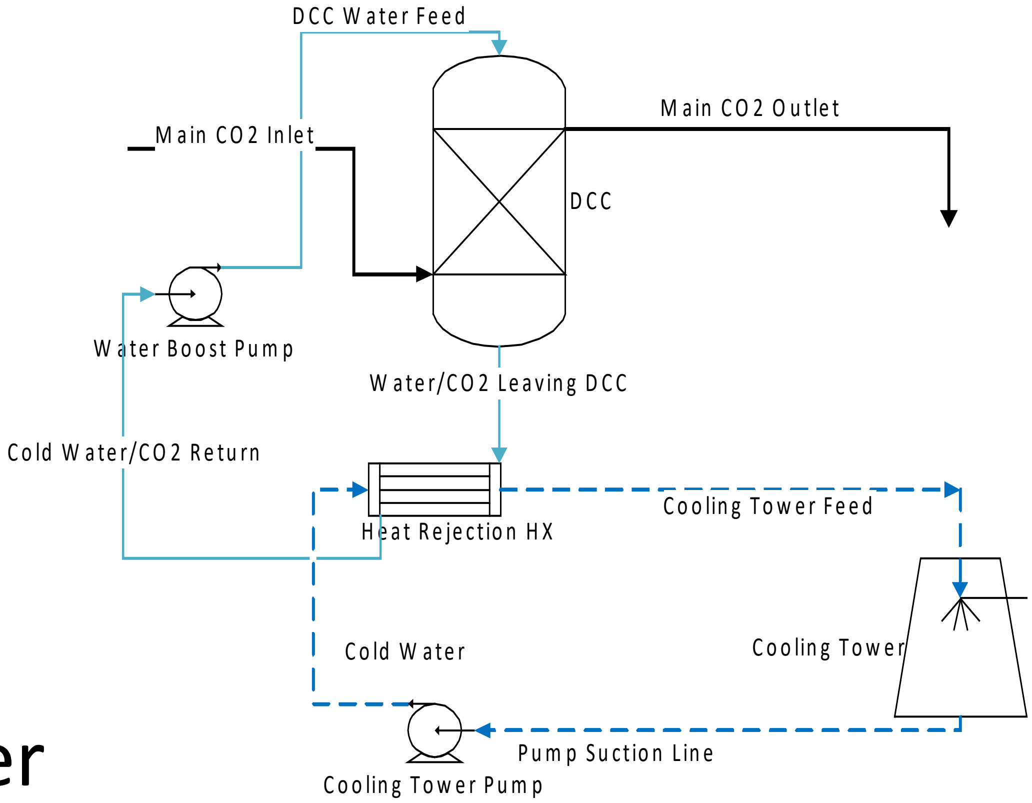
# Fuel Supply System

- Major challenge to supply oxygen to a 700°C flow
- Torch ignitor system



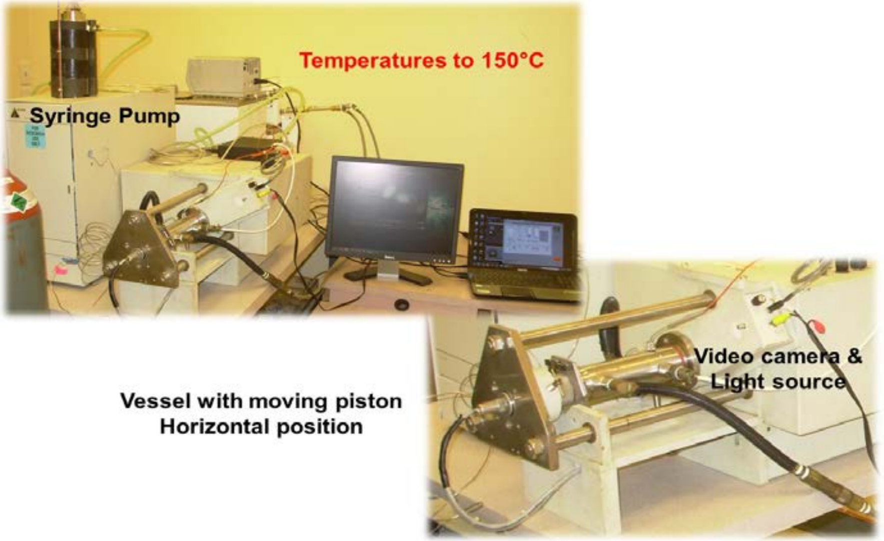
# Water Separation

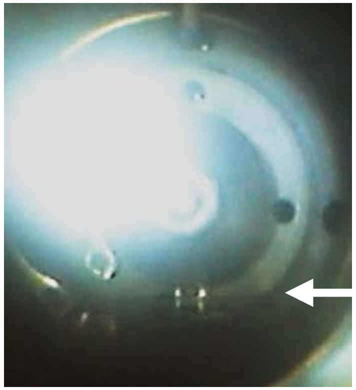
- Water is not particularly soluble in $CO_2$ below 100°C
- Cascaded water system prevents excess $CO_2$ loss from cooling water



# Water/$CO_2$ Equilibrium Testing

- Phase equilibrium test ongoing at Thar Energy
- Testing to confirm solubility limits of water in $CO_2$
- Needed for modeling of water seperation



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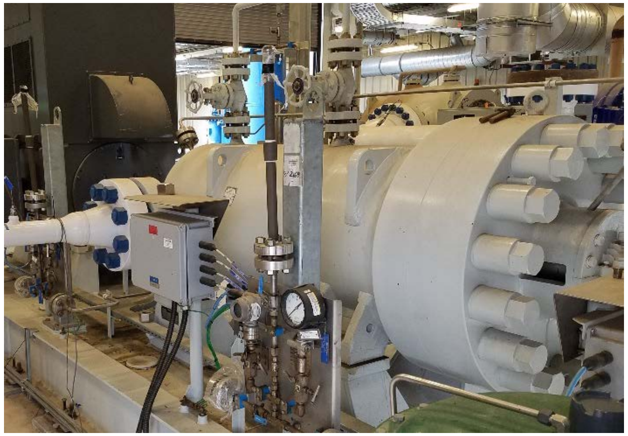
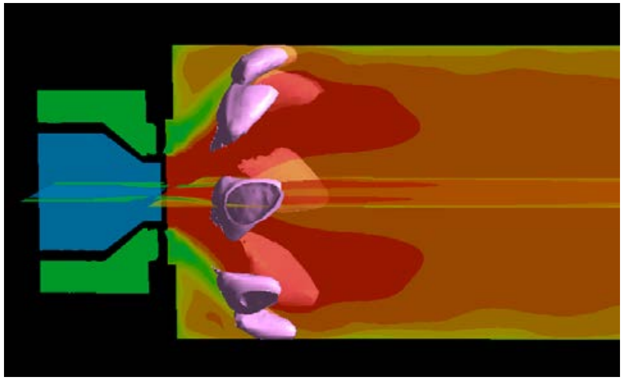
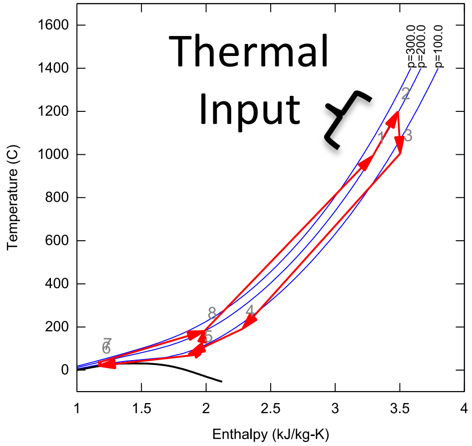
# Next Steps

- Finalize combustor design
  - Heat transfer
  - Injector design
  - Optical access
- Finalize quotes on loop and fuel systems
- Finalize combustor manufacturing plan

# QUESTIONS?






Thermal
Input
p=300.0
p=200.0
p=100.0
1
2
3
4
5
6
7
8
1600
1400
1200
1000
800
600
400
200
0
Temperature (C)
1
1.5
2
2.5
3
3.5
4
Enthalpy (kJ/kg-K)