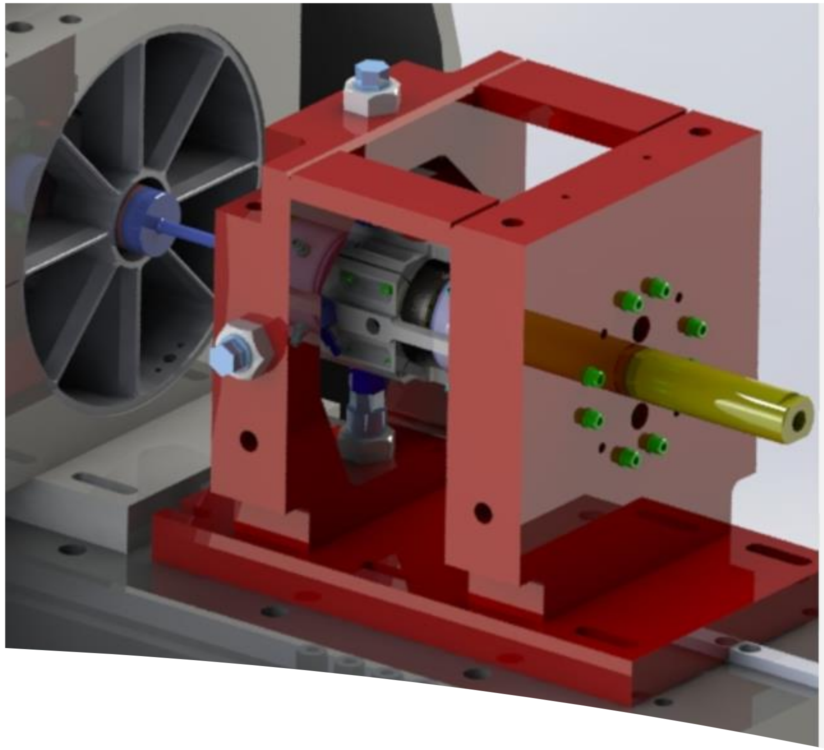

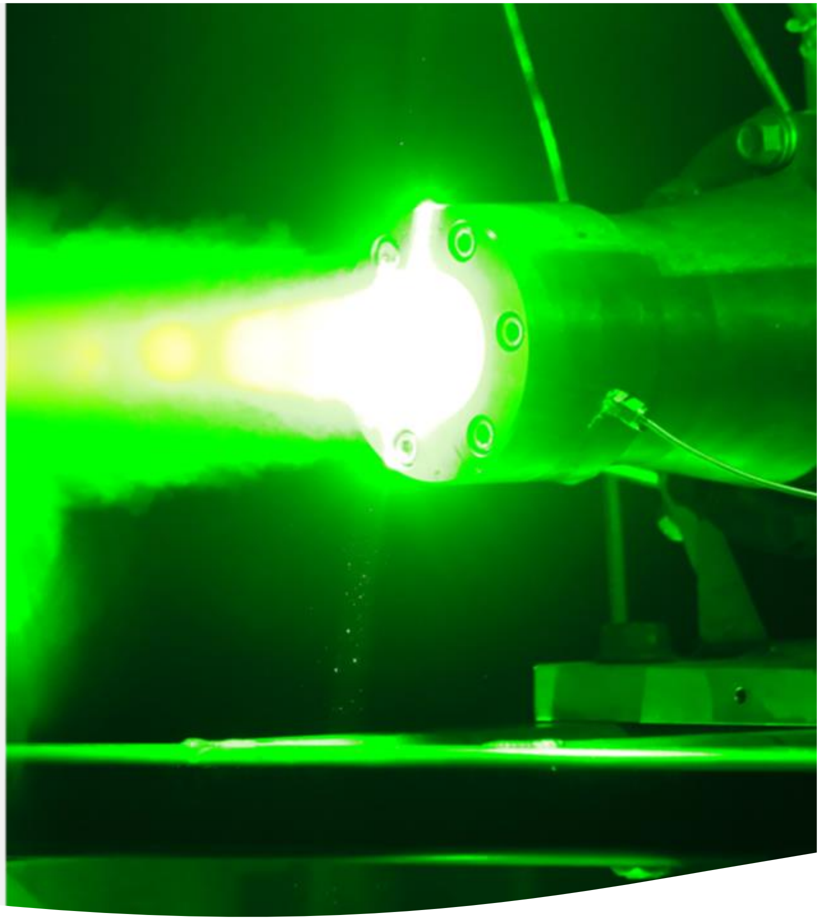

Design of a 1 MW Direct Fired Oxy-Fuel Combustor for sCO_2 Power Cycles

SwRI
SOUTHWEST RESEARCH INSTITUTE

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Georgia Tech

Air Liquide

Spectral Energies

UTSR University Turbine Systems Research

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Current Agenda:

- **Project Review**
  - Project Goals
  - Test Rig Overview
- **Design Review**
  - Combustor Design - CFD & Analysis Review
  - Light-off Conditions Cycle Modeling
- **Facility Status Update**

Project Objectives & Status

- Design a 1 MW thermal oxy-fuel combustor capable of generating 1200°C outlet temperature

  COMPLETE

- Manufacture combustor, assemble test loop, and commission oxy-fuel combustor

  IN PROCESS, 70% COMPLETE
  COMPLETION DATE: May 2023

- Evaluate and characterize combustor performance using temperature, pressure, and optical access for advanced diagnostics
  - Demonstrate closed-loop operability including light-off, combustion stability, and water separation
  - Achieve continuous operation of oxy-combustor design at full-scale pressure and temperature conditions
  - Validate oxy-combustion models for heat transfer, mixing, and critical reactions

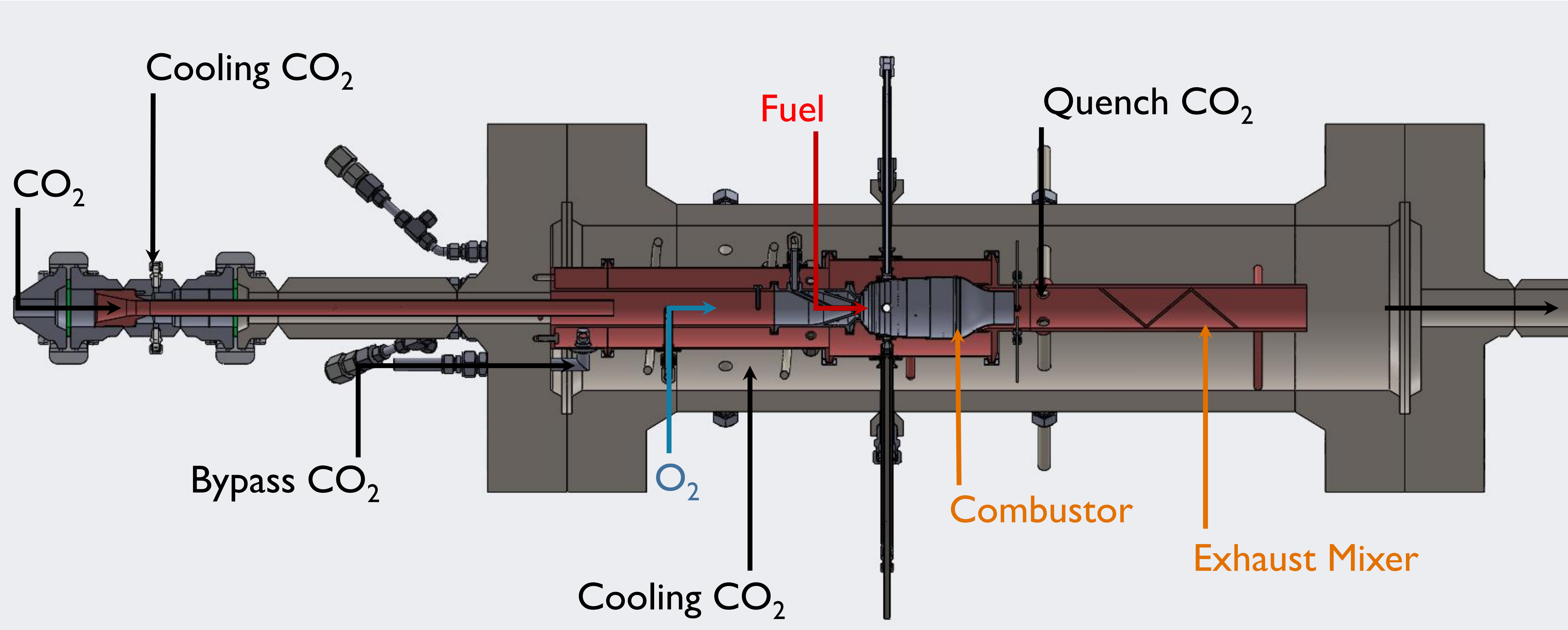
  COMPLETION DATE: December 2023

SOUTHWEST RESEARCH INSTITUTE

Combustor Test Rig

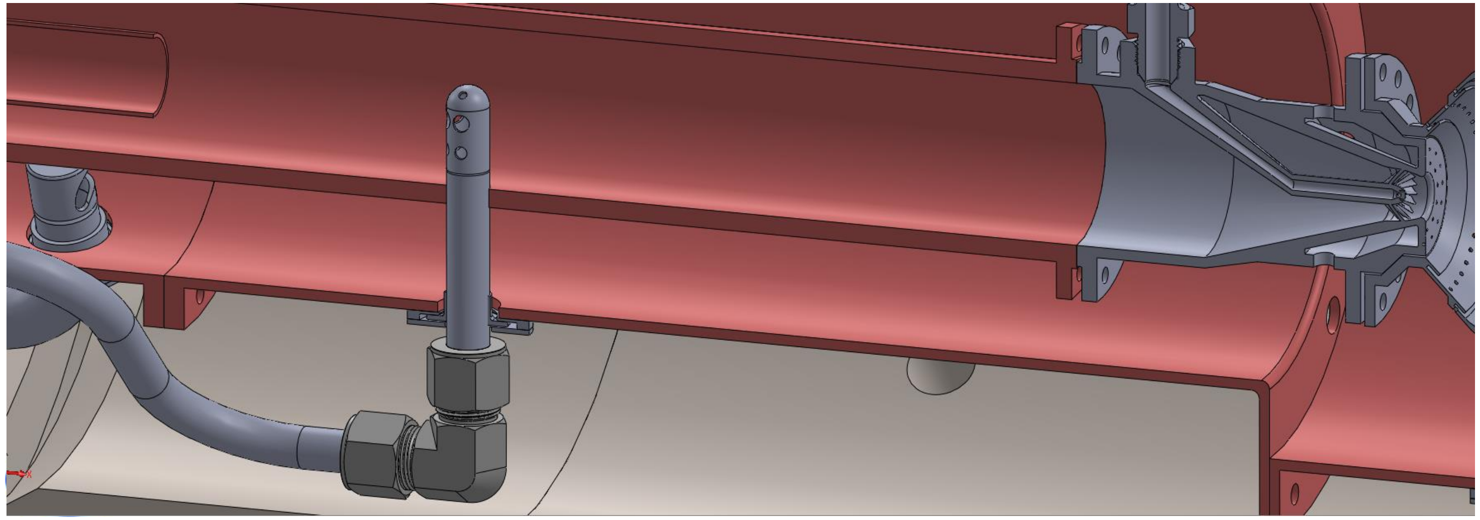
Overview

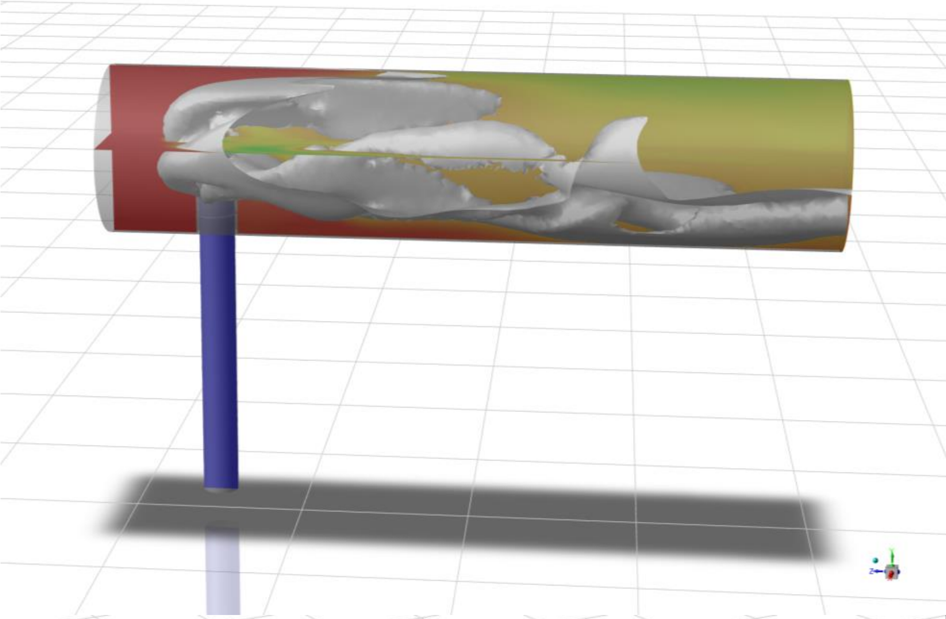
Combustor Schematic

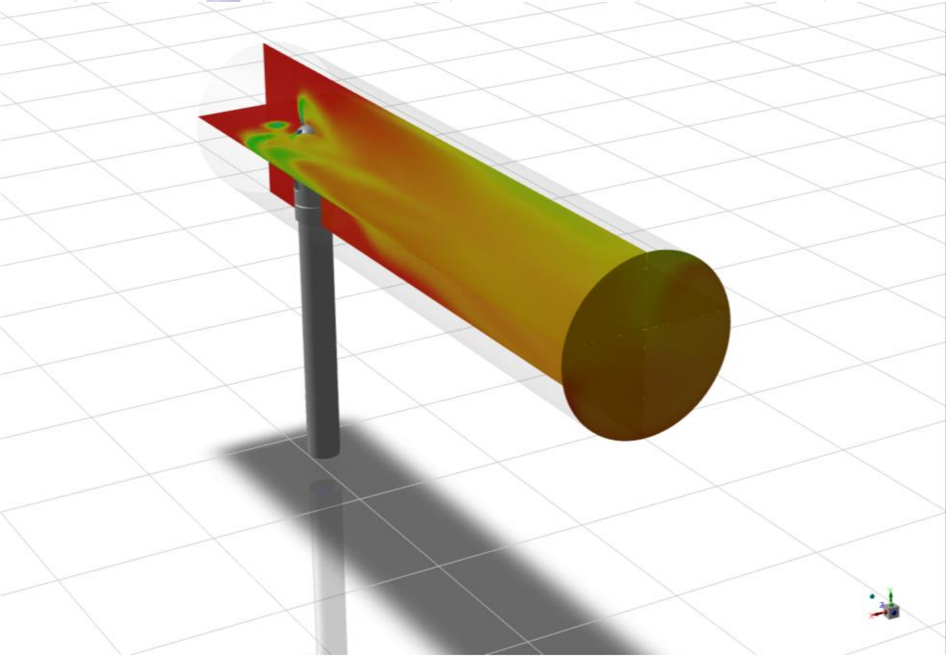


Oxygen System

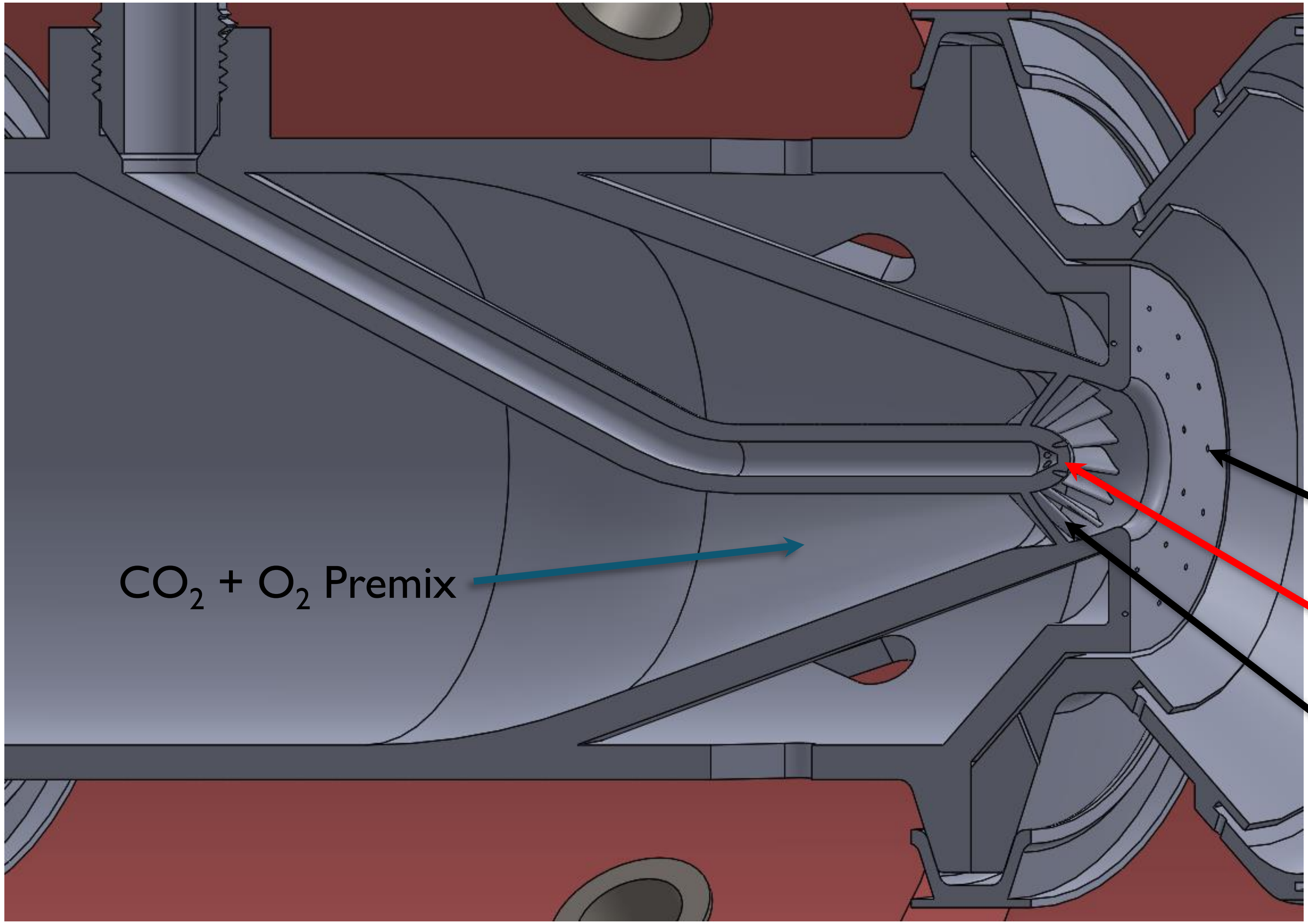
- Guidance from personnel at NASA Stennis and White Sands, review from project partner Air Liquide
- LOX tank with cryogenic pump and ambient vaporizer
- Oxygen injection upstream of fuel injector







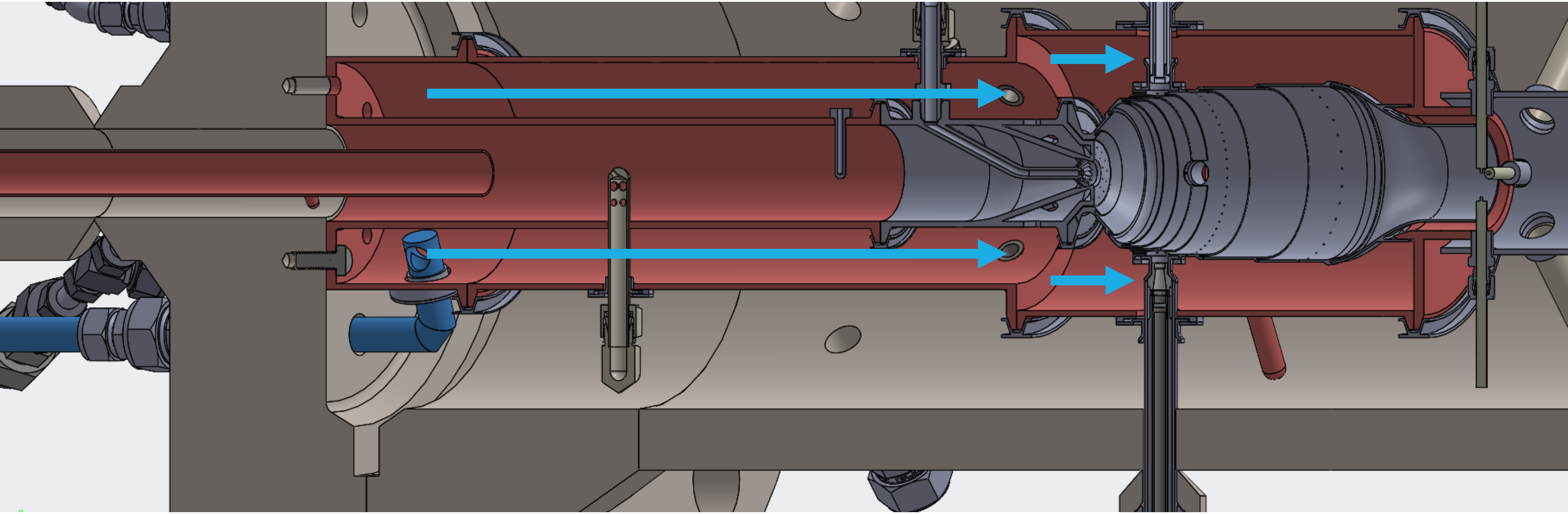
Fuel Injector



- Additively manufactured Haynes 282
- Swirl angle of inlet vanes chosen after literature review and CFD simulations

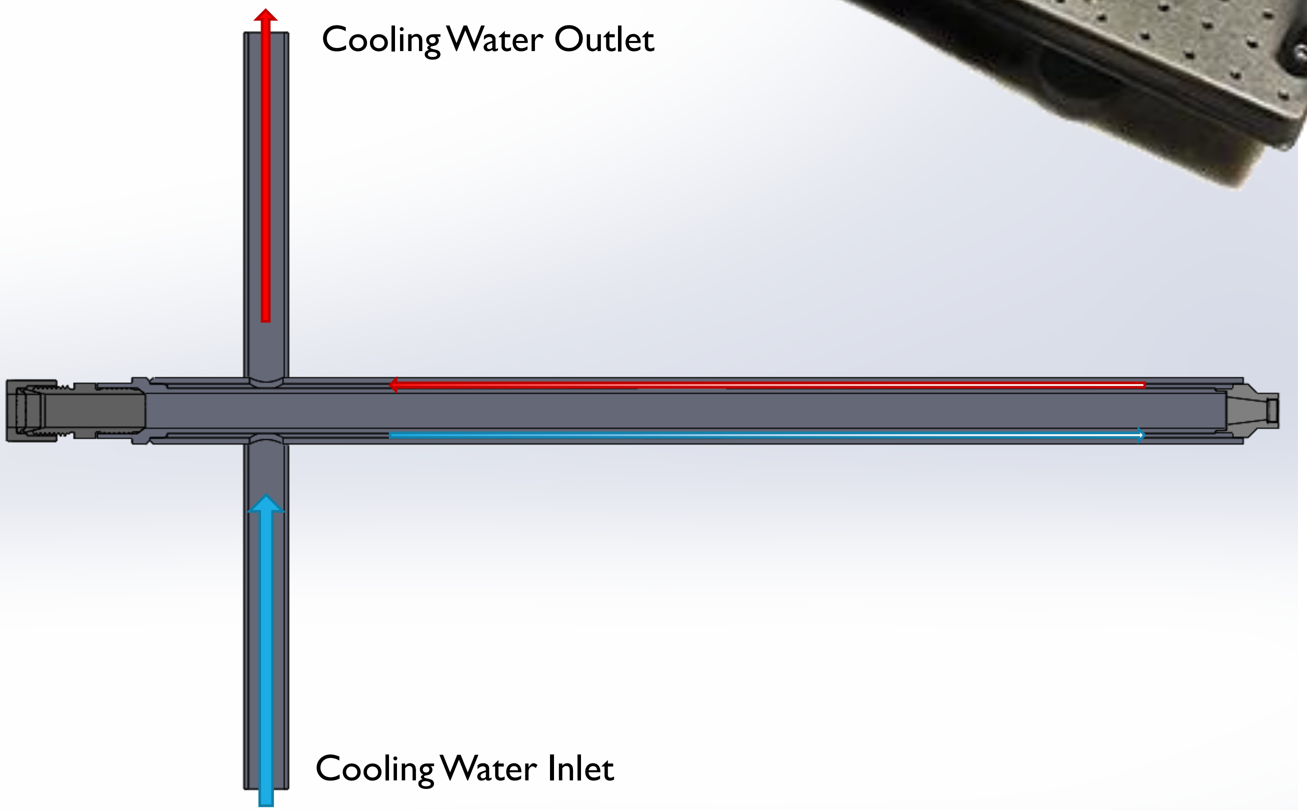
Combustor Cooling

CO_2 bypass gas enters annulus from a dedicated line (highlighted in blue) with flow control, allowing remote manipulation of combustor liner temperatures

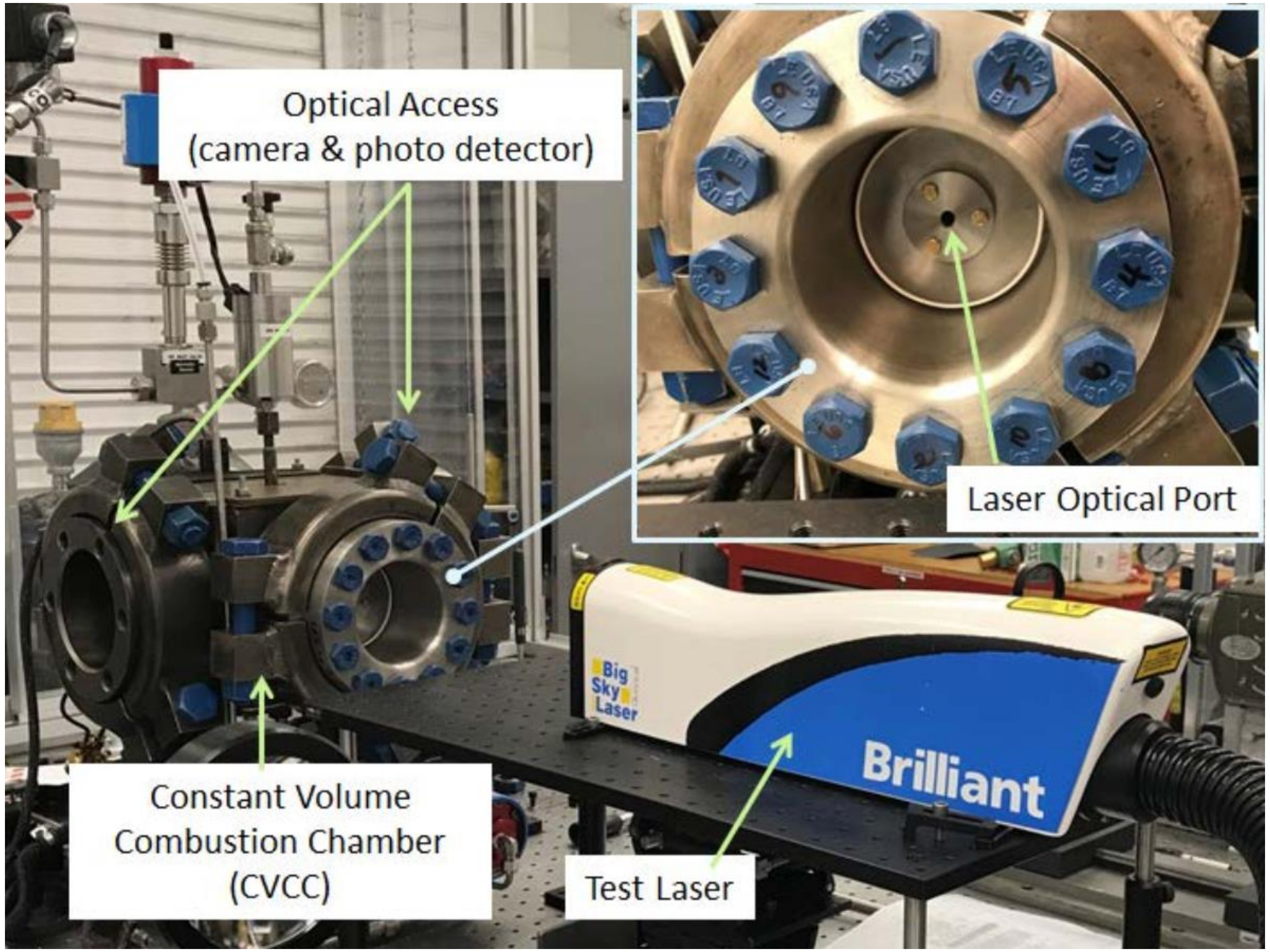


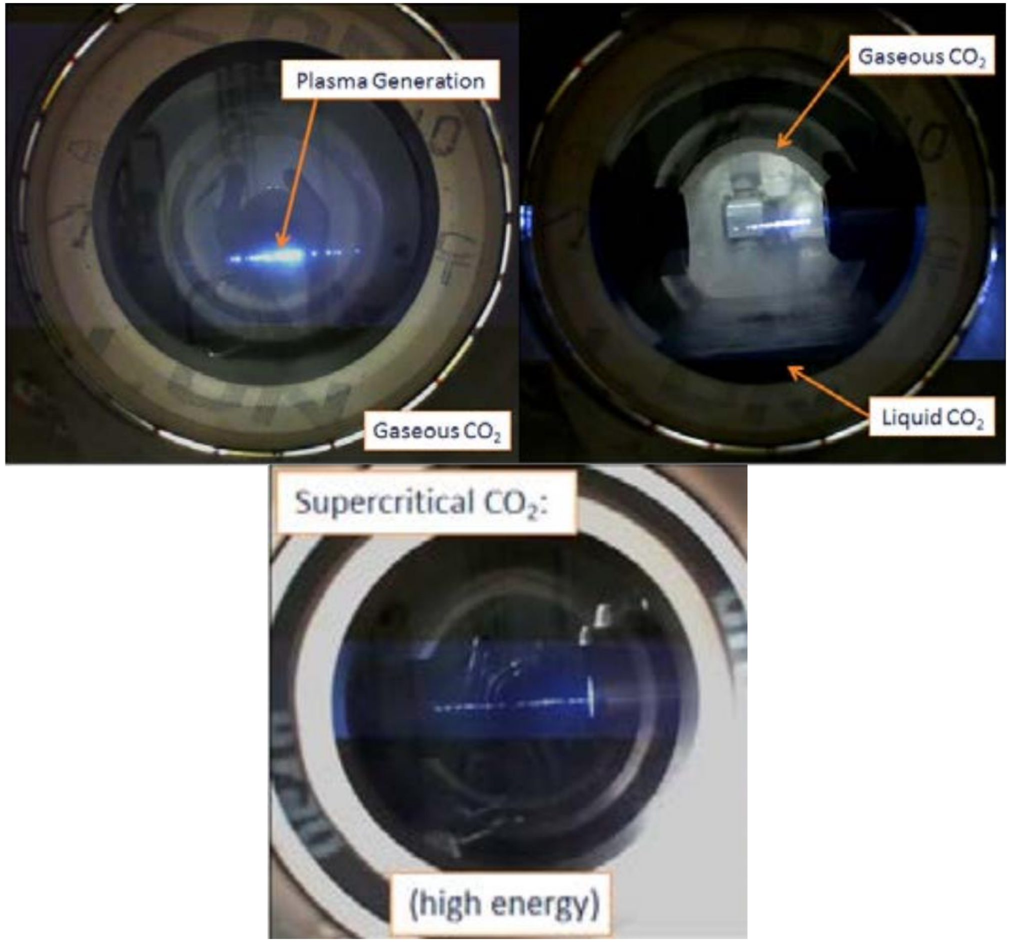
Laser Ignition System

- Class 4 Quantel Qsmart Twins
  - 380mJ @ 532nm, 10Hz
- Water cooled probe allows access to the combustor and keeps focal lens temperature low



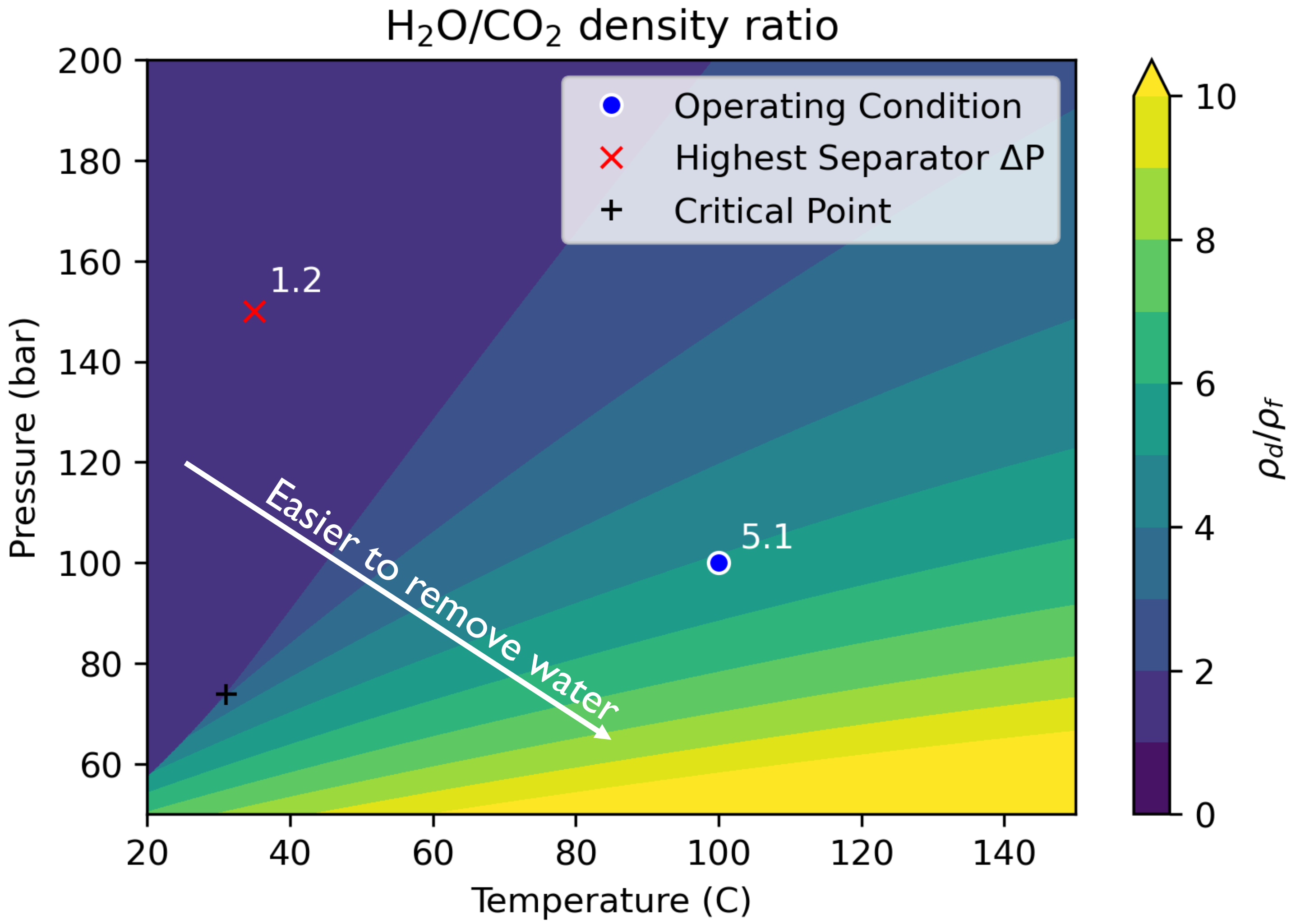
Previous Laser Ignition Tests

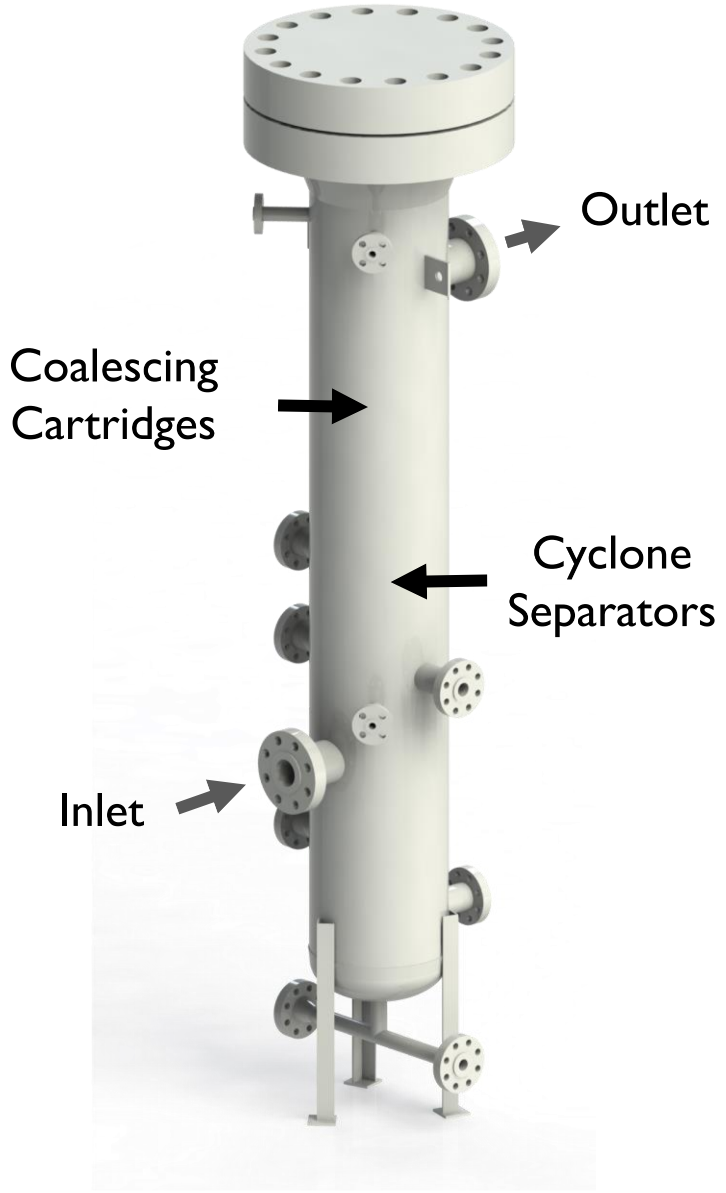




Katcher *et al.* 2019

Water Separator

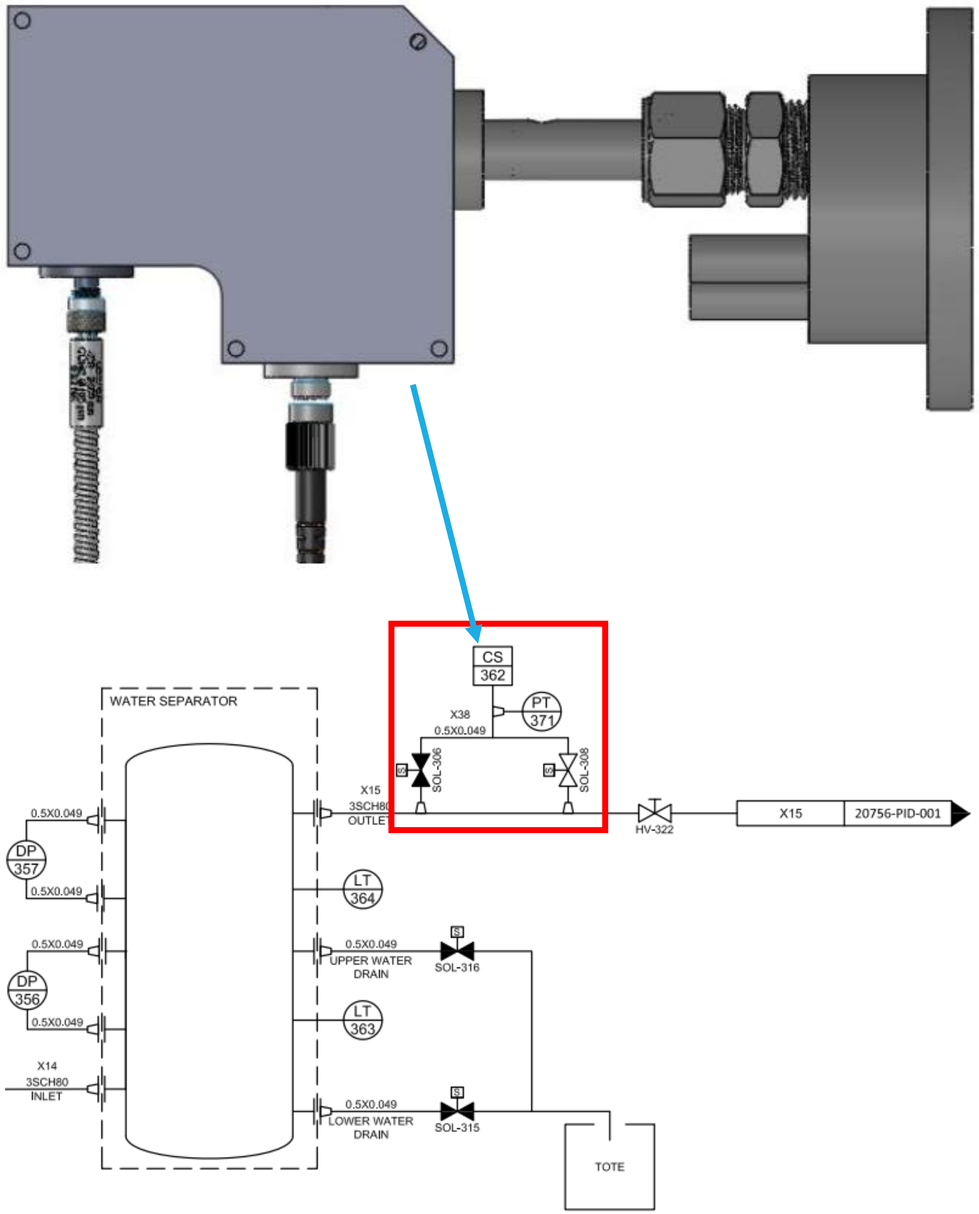




Other contaminants need to be sensed and removed as well!

Constituent Sensor

- Working with Sporian Microsystems to develop a constituent sensor to detect H_2O in the test loop using Raman spectroscopy.
- Highly accurate detection of H_2O in flowing sCO_2 confirmed at SwRI testing in March 2022.
- Alternatives exist, including Supercritical Fluid Chromatography (CFS) and Fourier Transfer Infrared (FTIR), and high-pressure oxygen sensors. FTIR is available on-site but limited to low pressure and O_2.



Combustor Modeling

Design Details

Chemical Kinetics

Georgia Tech and University of Central Florida each created combustion mechanisms for the sCO2 oxy-combustion system. Georgia Tech's model was ultimately selected on the balance of speed and accuracy.

Table 1-2. Computational Comparison between the 6-Species and 13-Species Simulations

Elements	Species	Equations	Processors	Time (s)	Time Factor
2.32E+06	6	2	15	3,852	1
2.32E+06	13	42	15	7,675	***2.0***
1.34E+06	6	2	15	2,081	1
1.34E+06	13	42	15	4,388	***2.1***

$$0.95\ CH_4 + 0.05\ C_2H_6 + 1.55\ O_2 \rightarrow 2.05\ H_2O + 1.05\ CO$$

$CO + 0.5\ O_2 \rightarrow CO_2$ → 41 equations from the skeletal model involving H, H_2, O, O_2, H_2O, H_2O_2, HO_2, OH, HCO, CO, and CO_2

Figure 1-2. The Conversion of the 6-Species Kinetic Model to a 13-Species Kinetic Model

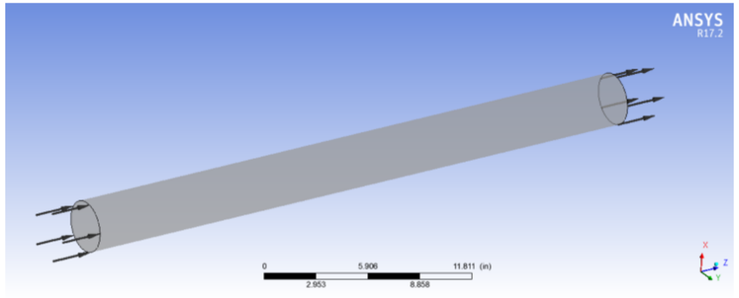


Figure 1-3. Simplified Premixed Reaction Chamber

Table 1-1. Premixed Chamber Inlet Species Mass Fractions

Component	Inlet Mass Fraction
C_2H_6	0.00113
CH_4	0.01148
O_2	0.05003
CO_2	0.93738

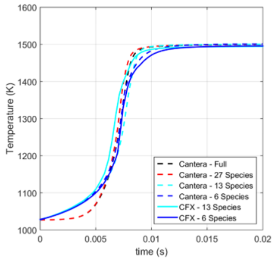


Figure 1-4. Predicted Temperature Versus Time Results

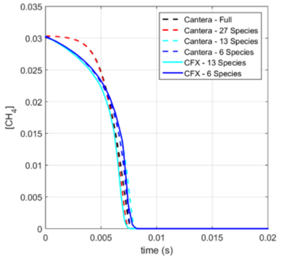


Figure 1-5. Predicted Mole Fraction CH_4 Versus Time Results

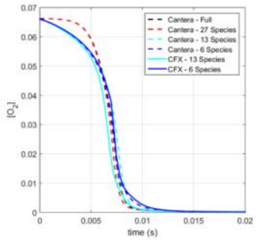


Figure 1-6. Predicted Mole Fraction O_2 Versus Time Results

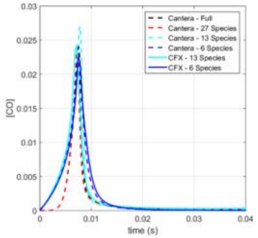


Figure 1-7. Predicted Mole Fraction CO Versus Time Results

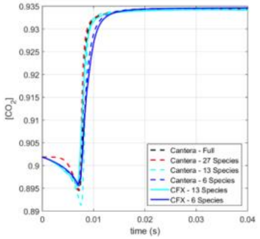


Figure 1-8. Predicted Mole Fraction CO_2 Versus Time Results

Grid Sensitivity

- The chemical kinetic simulations also explored grid dependence.
- A 13 species mechanism was used.
- Grid size requirements are dependent in part on turbulence models.
- Additional grid refinement was performed when switching from steady to unsteady flow simulations.

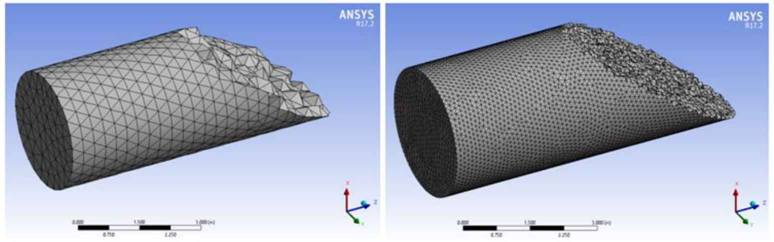


Figure 1-9. Examples of Coarse (left) and Fine (right) Meshing Results for Premixed Chamber

Table 1-3. Mesh Statistics for Premixed Chamber

Elements	Element Multiplication Factor
0.05E+06	1.0
0.40E+06	8.0
0.85E+06	17.0
1.30E+06	26.0
2.30E+06	46.0
1.34E+06	26.8
6.17E+06	122.0

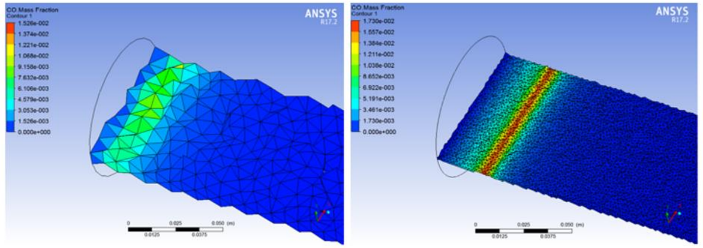


Figure 1-13. CO Mass Fractions Contoured to Show the Grid Resolution of the Combustion Reaction. Coarse Grid (left) and Fine Grid (right)

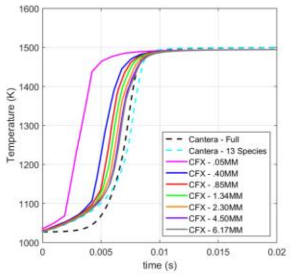


Figure 1-10. Predicted Temperature Versus Time Results for Various Resolutions

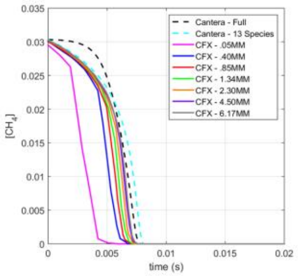


Figure 1-11. Predicted Mole Fraction of CH_4 Versus Time Results for Various Resolutions

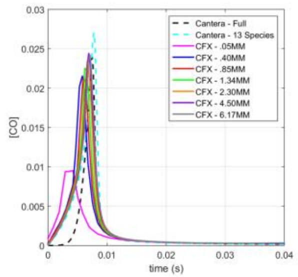
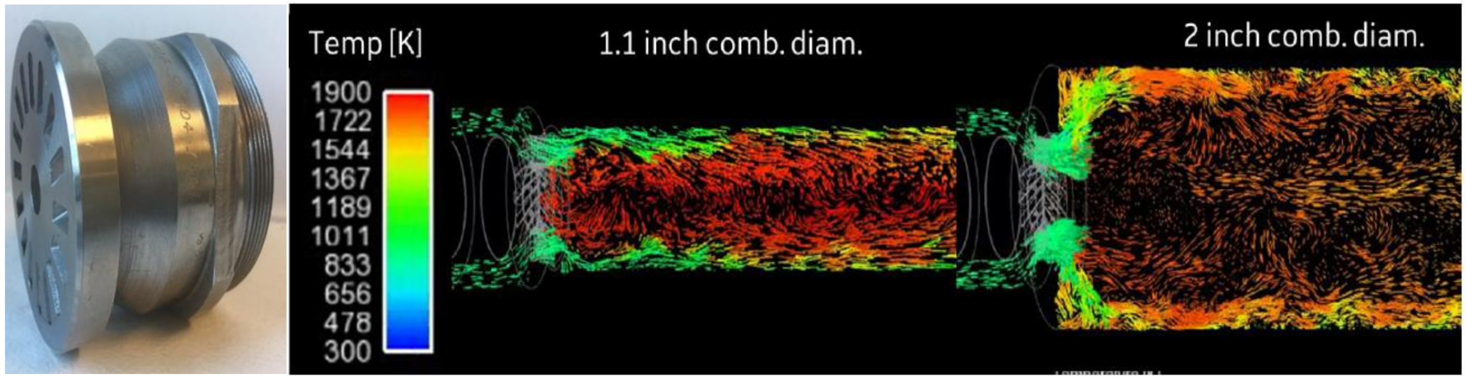
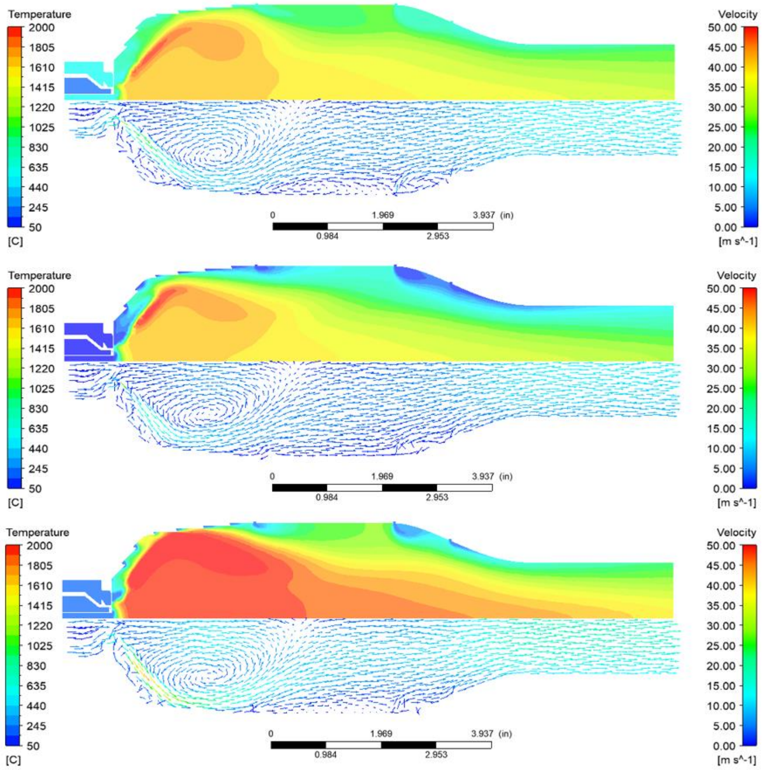


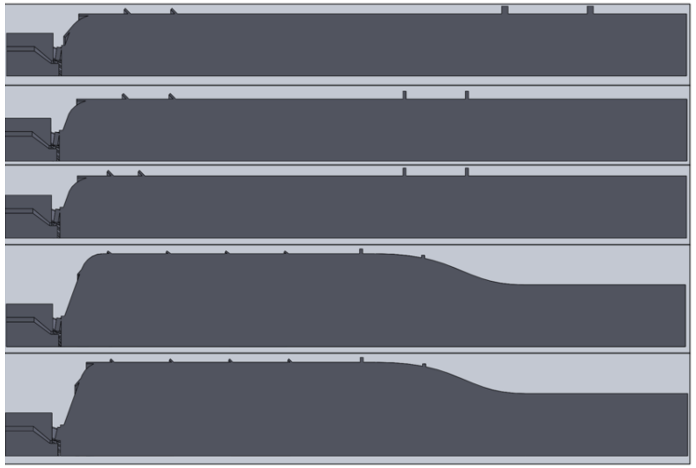
Figure 1-12. Predicted Mole Fraction of CO Versus Time Results for Various Resolutions

Flow Field



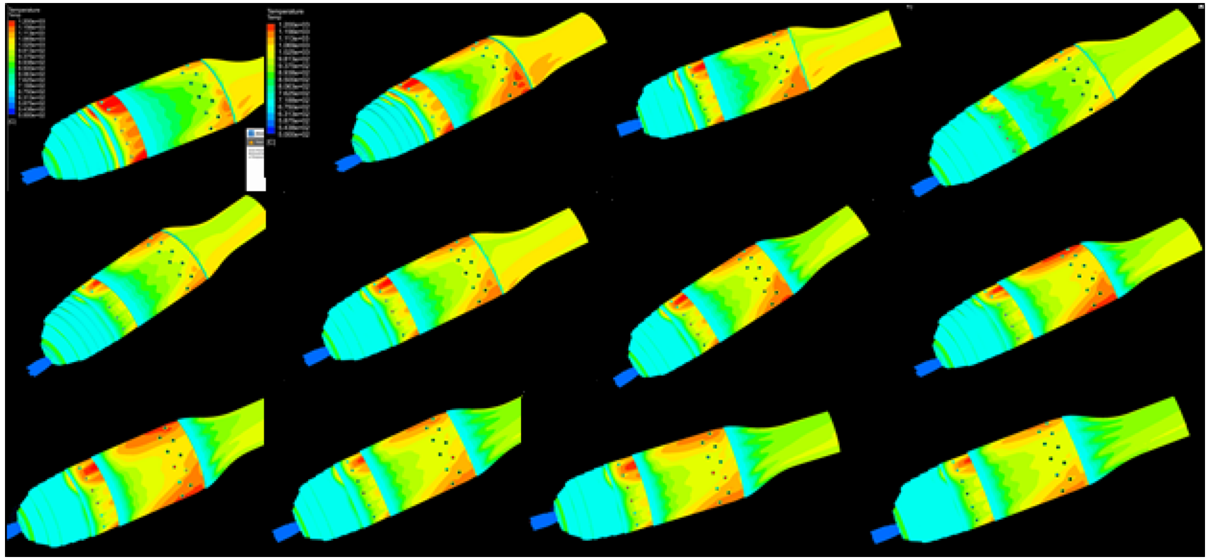
- Combustor design adapted from an older GE approach, but has changed significantly.
- Flame stability relies on swirl and cooling hole recirculation control.
- Light-off simulations have not yet been conducted at **low temperatures and pressures using real gas effects**

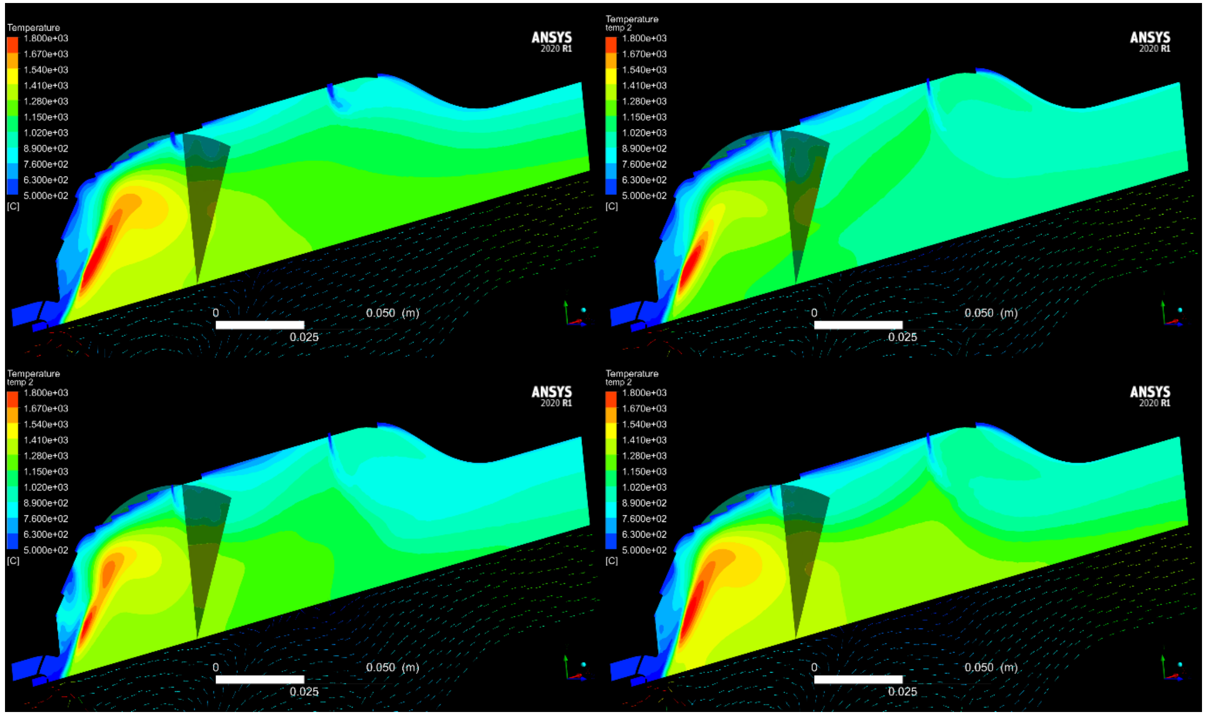


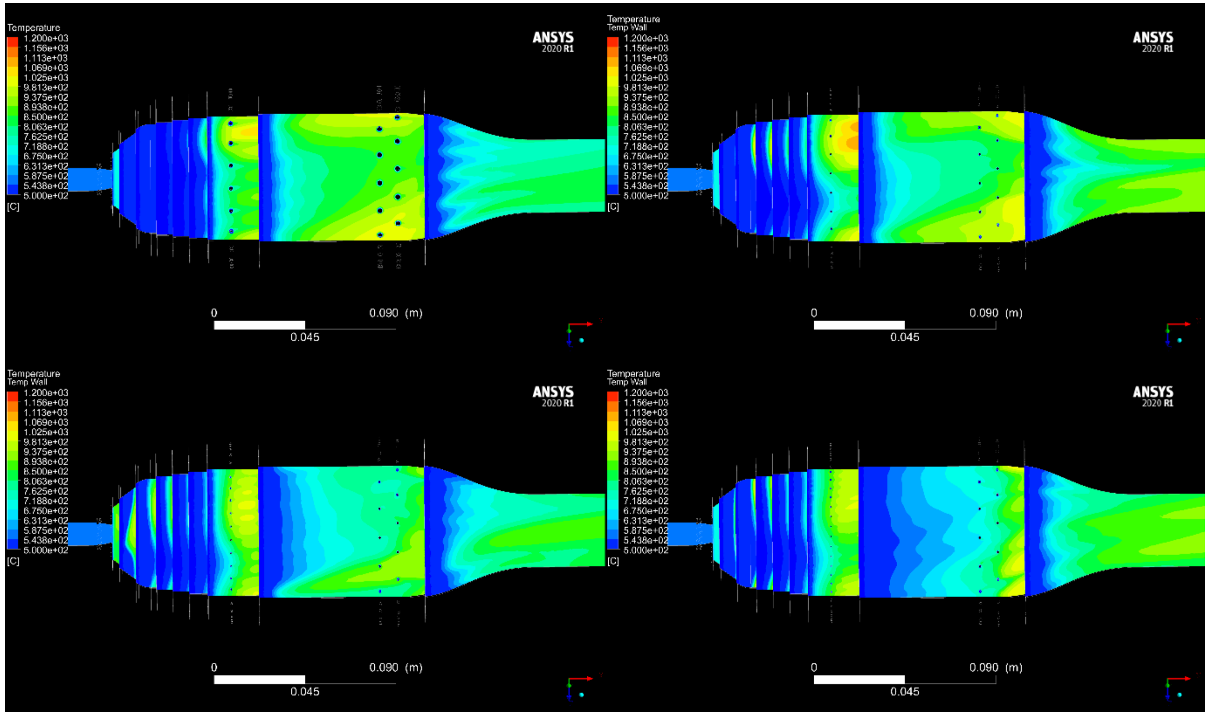


Design and Optimization

Preliminary approaches explored the design space using low-cost, <u>low-fidelity</u> steady RANS simulations.

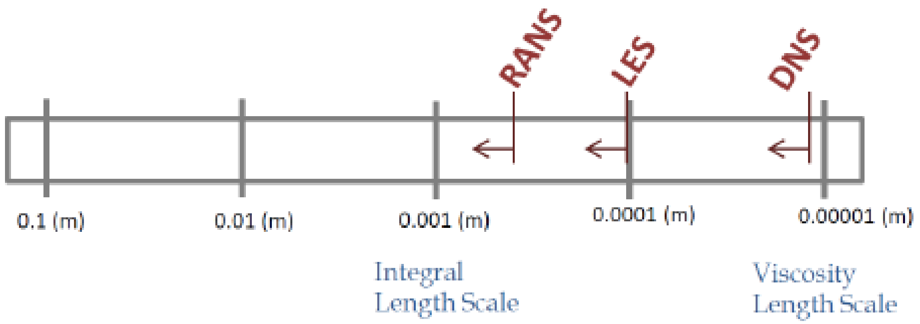


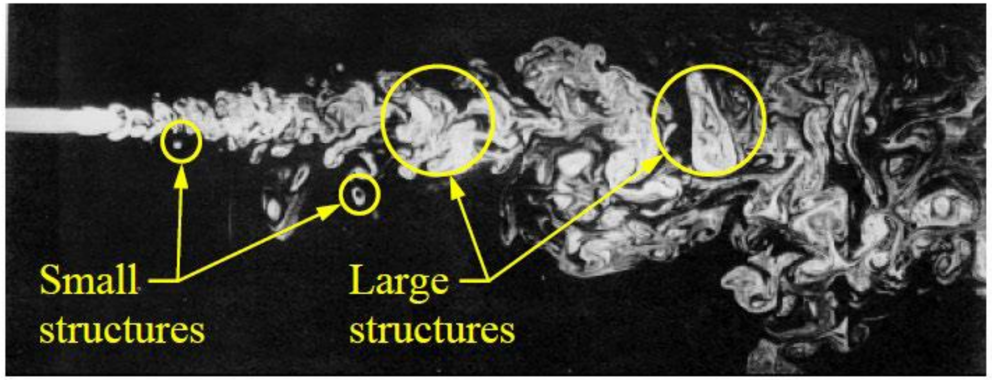




Turbulence Modeling

- Two approaches over the design cycle
  - **Steady Reynolds-Averaged Navier-Stokes (RANS):** This model is used to account for mixing by introducing turbulent diffusion coefficients for momentum, energy, and species
  - **Unsteady Detatched Eddy Simulations (DES):** Resolves the large length scale like LES and models the small, near-wall length scale like RANS
- Turbulence Chemical Interactions **not yet modeled, only assuming laminar flame speeds, currently investigating this liability.**



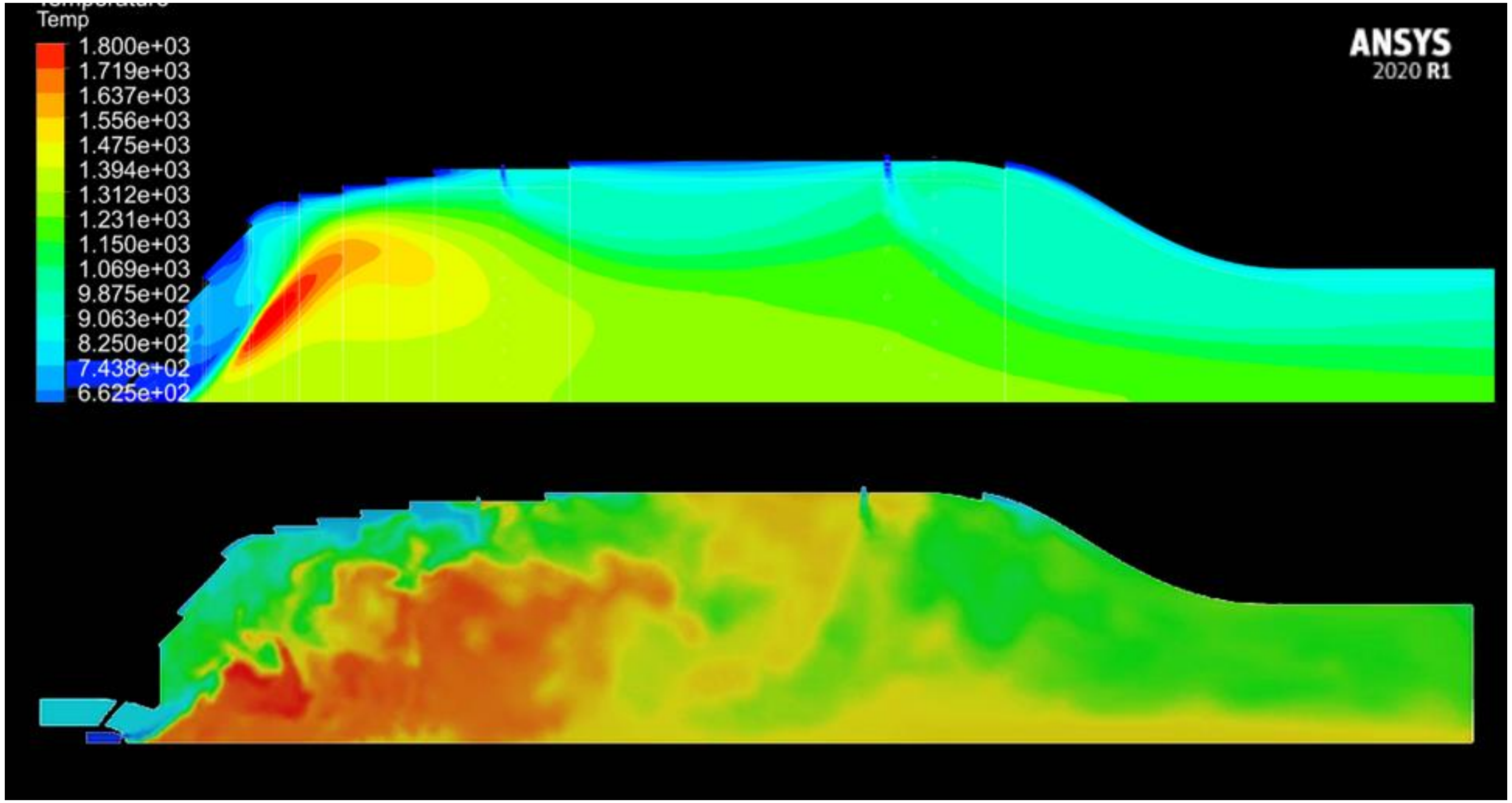


CONVERGECFD

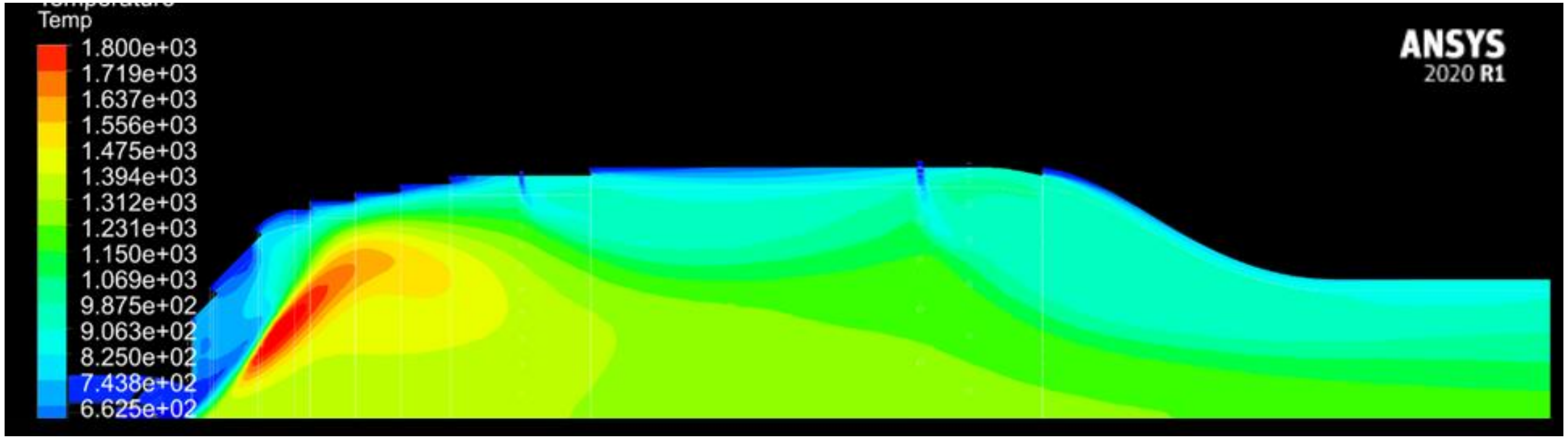
Steady vs. Unsteady Modeling

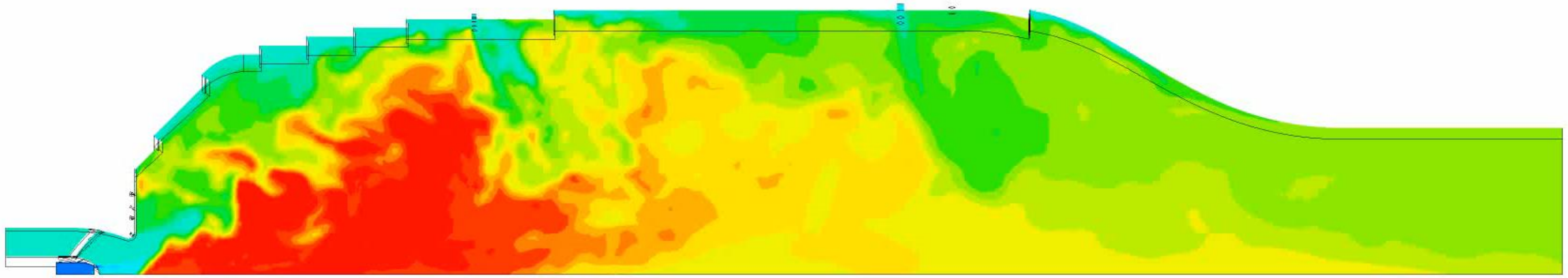
Steady RANS Simulation

Unsteady DDES Simulation
(~5-10x cost per run)

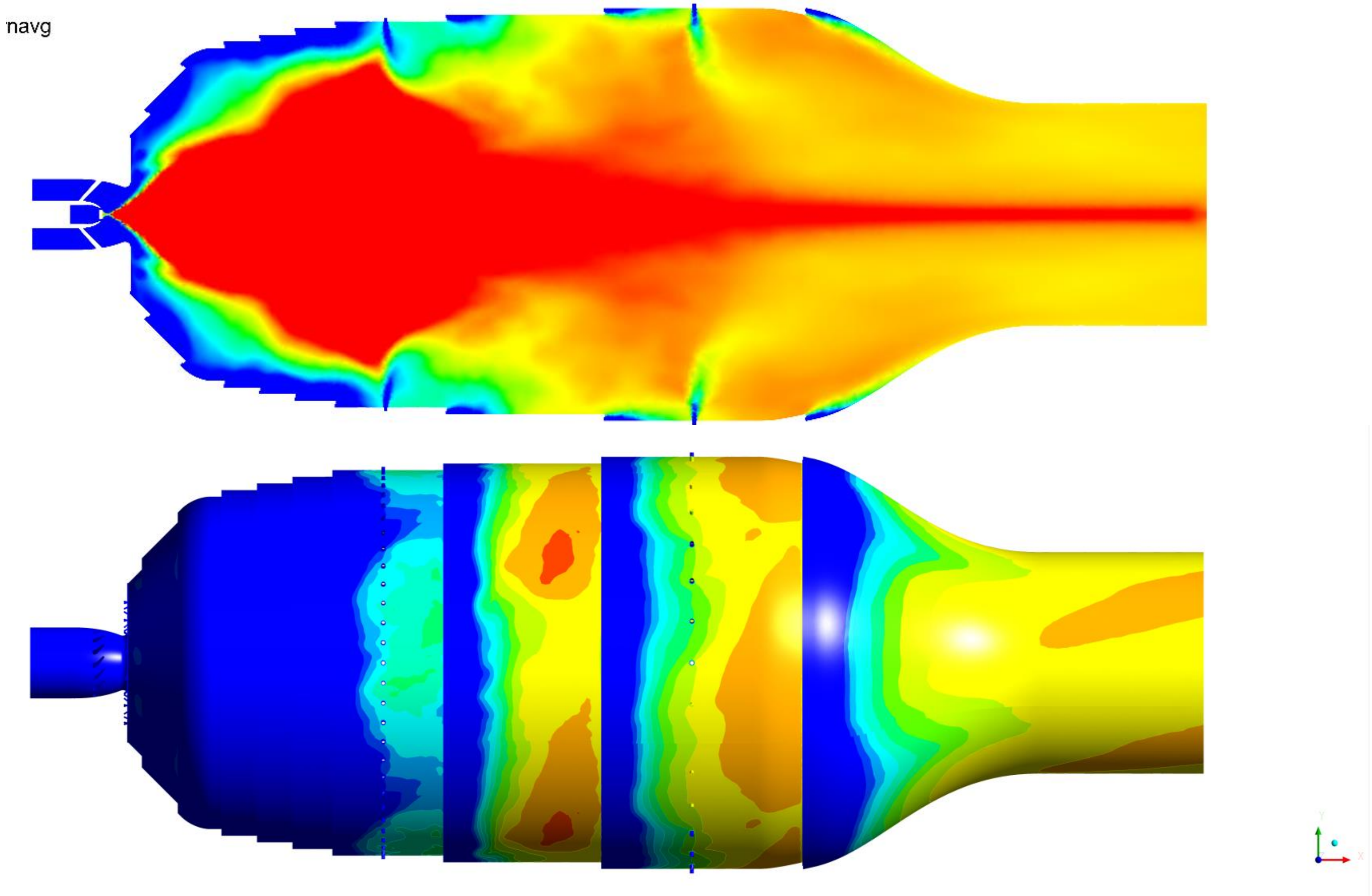


Unsteady Combustion Simulations





Time-averaged DES results



Light-Off Conditions

Literature Review & Cycle Modeling

Light-Off: Open Loop

Nominal Targets	1	2	3	4	5	6	7	8	9
Substance	CO2	CO2	CO2	CO2	O_2	CO2	Methane	CO2	CO2
Function	Main Loop Inlet	Inlet Thermal Cooling	Instrumentation Quench	Combustor Cooling	Oxidizer	Casing Cooling	Fuel	Exhaust Quench	Loop Exit
Pressure [psi]	247	270	270	270	300	270	300	270	240
Temp [°C]	149	90	90	90	50	90	50	90	405
Flowrate [lbm/s]	0.041	0	0	0.209	0.00765	0	0.00189	0	0.260

43 kW combustion

		Temperature [C	Pressure [Bar]	Enthalpy [kJ/kg]	State
State 1	Compressor Inlet	33.00	15.60	499.08	Superheated gas
State 2	Compressor Outlet	38.00	17.60	501.99	Superheated gas
State 3	Recycle valve inlet	38.00	17.60	501.99	Superheated gas
State 4	Recycle Valve outlet	36.29	15.88	501.99	Superheated gas
State 5	Quench line	38.00	17.60	501.99	Superheated gas
State 6	Recuperator HP Inlet	38.00	17.60	501.99	Superheated gas
State 7	Recuperator HP Outle	#[PHFLSH error 2	17.50	#VALUE!	#VALUE!
State 8	Cool line	38.00	17.50	502.09	Superheated gas
State 9	Heater Inlet	38.00	17.50	502.09	Superheated gas
State 10	Heater Outlet	149.37	17.25	611.31	Superheated gas
State 11	Combustor Inlet	149.37	17.25	611.31	Superheated gas
State 12	Combustor Outlet	407.02	17.23	885.26	Superheated gas
State 13	Throttle Valve Inlet	407.02	17.23	885.26	Superheated gas
State 14	Throttle Valve Outlet	407.02	17.23	885.26	Superheated gas
State 15	Recuperator LP Inlet	407.02	17.23	885.26	Superheated gas
State 16	Recuperator LP Outlet	#[PHFLSH error 2	15.13	#VALUE!	#VALUE!
State 17	Seperator Inlet	#[PHFLSH error 2	15.13	#VALUE!	#VALUE!
State 18	Seperator outlet	#VALUE!	85.00	#VALUE!	#VALUE!
State 19	Cooler Inlet	36.29	15.88	501.99	Superheated gas
State 20	Cooler Outlet	33.00	15.60	499.08	Superheated gas

Fluid	CO2			
CO2	CO2;H2O|.9925;.0075 mass			
Compressor Flow Rate [kg/s]	Compressor Flow Rate [lb/s]			
1.81	4			
	71.2			
Loop Flow Rate [kg/s]				
1.81				
Percentage of compressor recycl	Percentage of HP Flow through recu	Percentage of Flow through heater		
94%	6%	1%	quench flow	
3.75	0.25	0.041	0	lb/s
Cooler Duty Required [kW]	Recup HP outlet Temp [C]	Combustor Main Inlet [C]		
4.96	#[PHFLSH error 248] Single-phase it	149.37		
Energy added by heater [kW]				
2.03				
Manual Inputs				
Critical Outputs				

States in yellow are not active open loop

Swap to Closed Loop

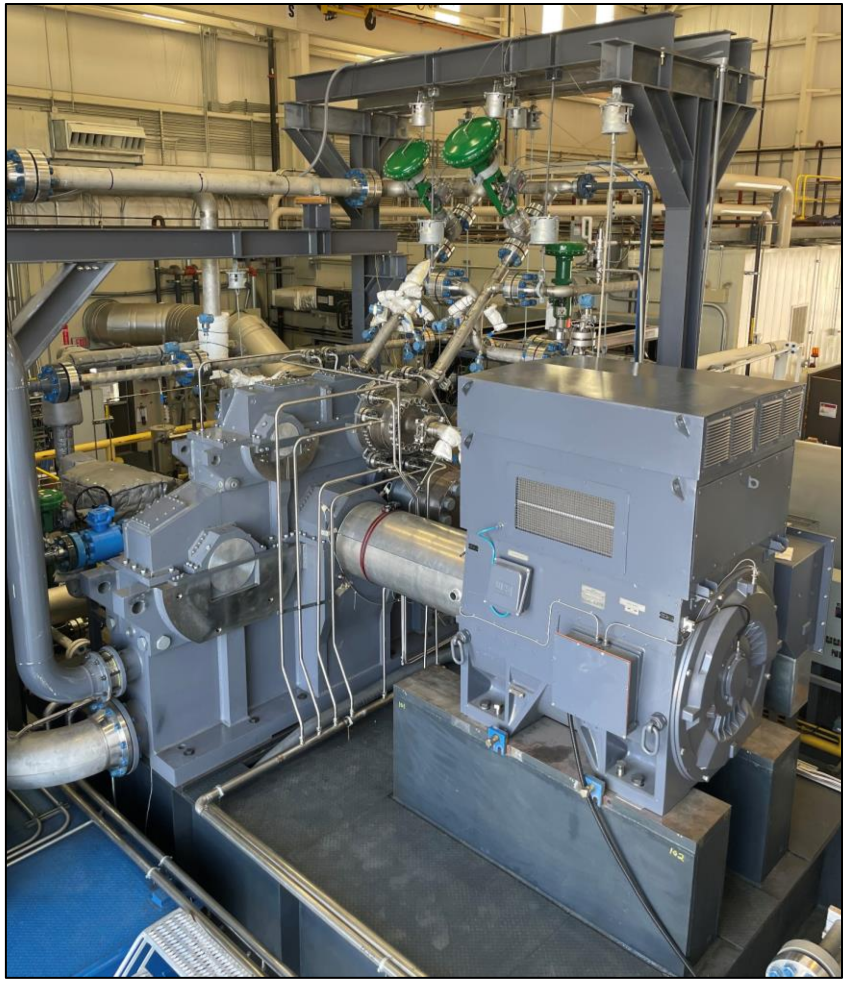
Nominal Targets	1	2	3	4	5	6	7	8	9
Substance	CO_2	CO_2	CO_2	CO_2	O_2	CO_2	Methane	CO_2	CO_2
Function	Main Loop Inlet	Inlet Thermal Cooling	Instrumentati on Quench	Combustor Cooling	Oxidizer	Casing Cooling	Fuel	Exhaust Quench	Loop Exit
Pressure [psi]	247	270	270	270	300	270	300	270	240
Temp [°C]	149	117	38	117	50	117	50	38	127
Flowrate [lbm/s]	0.041	0	0.05	0.209	0.00765	.75	0.00189	0.95	2.010

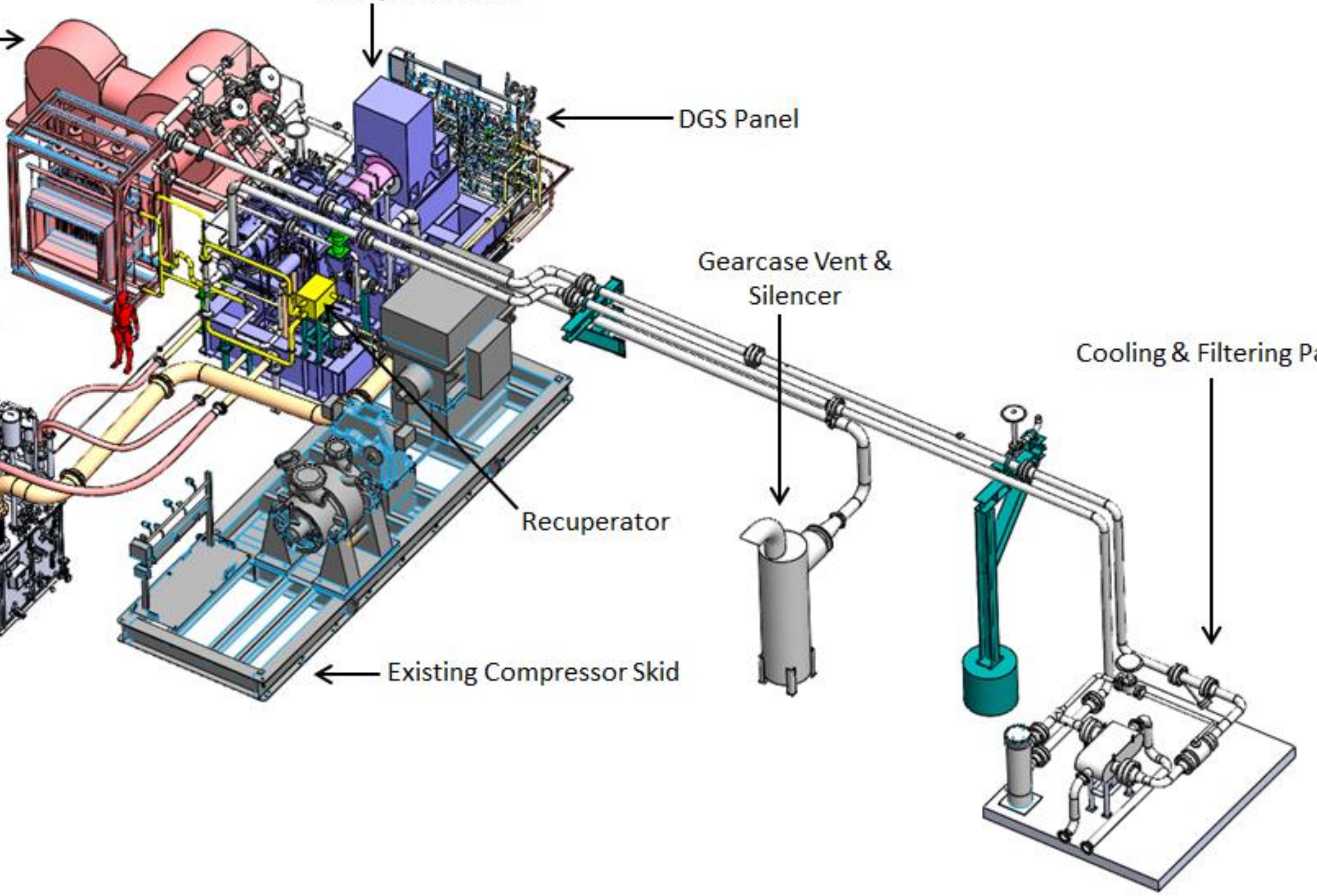
		Temperature [C]	Pressure [Bar]	Enthalpy [kJ/kg]	State		Fluid	CO2			
							CO2	CO2;H2O|.9925;.0075 mass			
State 1	Compressor Inlet	33.00	15.60	499.08	Superheated gas						
State 2	Compressor Outlet	38.00	17.60	501.99	Superheated gas		Compressor Flow Rate [kg/s]	Compressor Flow Rate [lb/s]			
State 3	Recycle valve inlet	38.00	17.60	501.99	Superheated gas		1.81	4			
State 4	Recycle Valve outlet	36.29	15.88	501.99	Superheated gas			42.5/71.2			
State 5	Quench line	38.00	17.60	501.99	Superheated gas		Loop Flow Rate [kg/s]				
State 6	Recuperator HP Inlet	38.00	17.60	501.99	Superheated gas		1.81				
State 7	Recuperator HP Outlet	117.01	17.50	579.17	Superheated gas						
State 8	Cool line	117.01	17.50	579.17	Superheated gas		Percentage of compressor recycle	Percentage of HP Flow through recup	Percentage of Flow through heater		
State 9	Heater Inlet	117.01	17.50	579.17	Superheated gas		50%	25%	1%	quench flow	
State 10	Heater Outlet	150.15	17.25	612.09	Superheated gas		2	1	0.041	1	lb/s
State 11	Combustor Inlet	150.15	17.25	612.09	Superheated gas						
State 12	Combustor Outlet	126.50	17.23	588.65	Superheated gas		Cooler Duty Required [kW]	Recup HP outlet Temp [C]	Combustor Main Inlet [C]		
State 13	Throttle Valve Inlet	126.50	17.23	588.65	Superheated gas		51.80	117.01	150.15		
State 14	Throttle Valve Outlet	125.97	16.23	588.65	Superheated gas						
State 15	Recuperator LP Inlet	125.97	16.23	588.65	Superheated gas						
State 16	Recuperator LP Outlet	86.50	16.13	550.25	Superheated gas		Energy added by heater [kW]				
State 17	Seperator Inlet	86.50	16.13	550.25	Superheated gas		0.61				
State 18	Seperator outlet	86.74	15.88	550.64	Superheated gas						
State 19	Cooler Inlet	62.88	15.88	527.63	Superheated gas						
State 20	Cooler Outlet	33.00	15.60	499.08	Superheated gas						
							Manual Inputs				
							Critical Outputs				
inputs displayed				kg/s							
Heater eff	3%		Recup HP flow	0.45							
Heater flame temp	1050.00		Recup LP flow	0.91	<-- Separator ~ 8						
Recup load	35										

Facility Status

Procurement & Fabrication

Fully Commissioned sCO_2 Compressor Loop

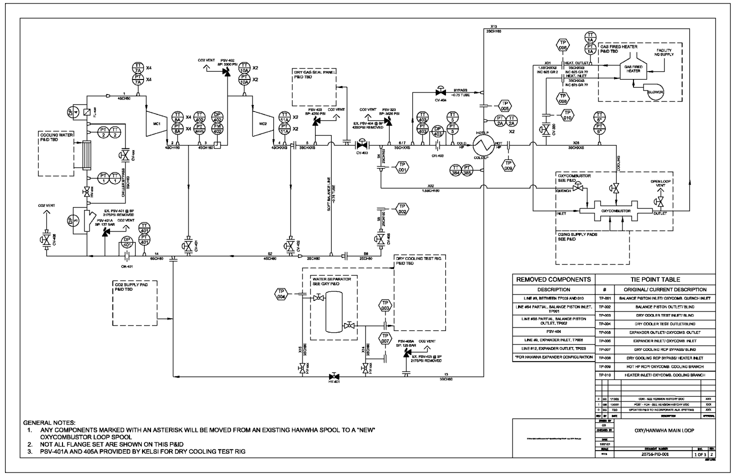


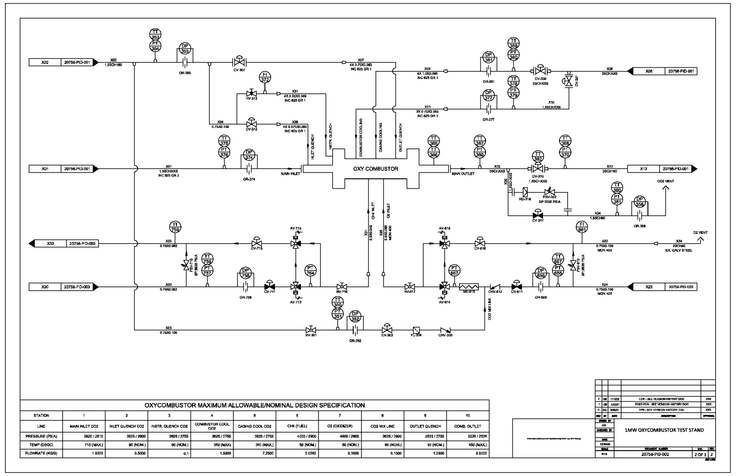


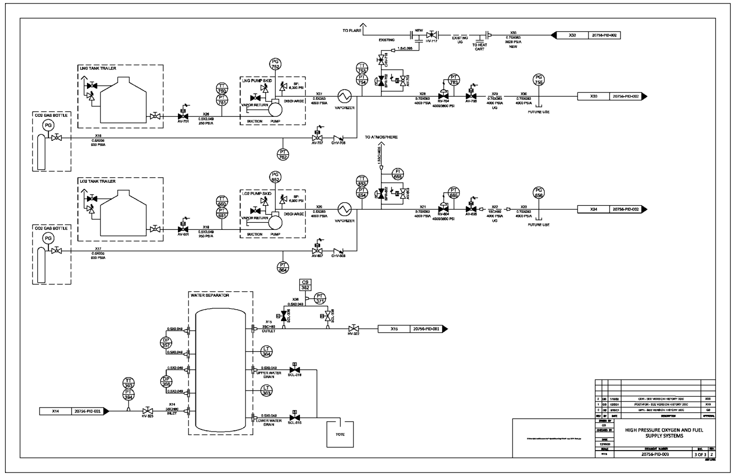
Flow Control Hardware

Purchased Components:

- Control Valves
- Actuated Valves
- Hand Valves
- Check Valves
- Orifice Flow Meters
- Pressure Regulators
- Pressure Safety Valves



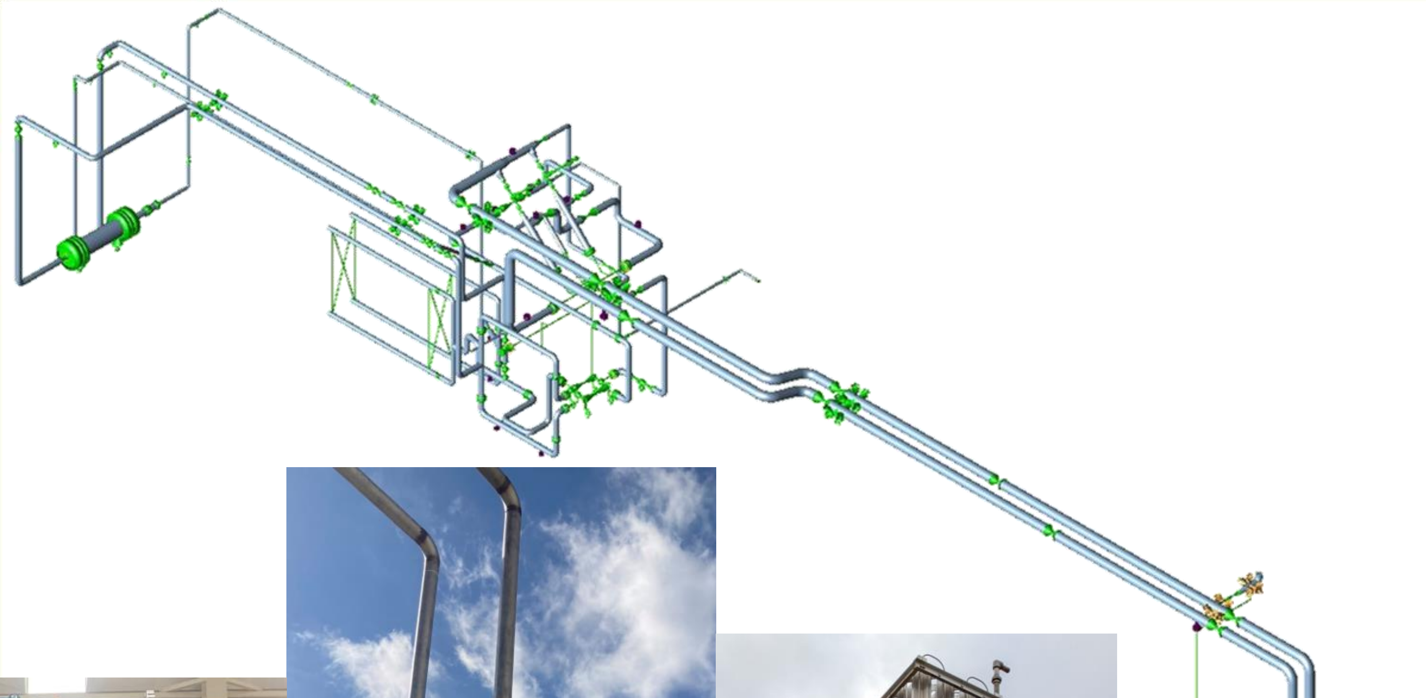




Piping & Supply Lines

Completed Components:

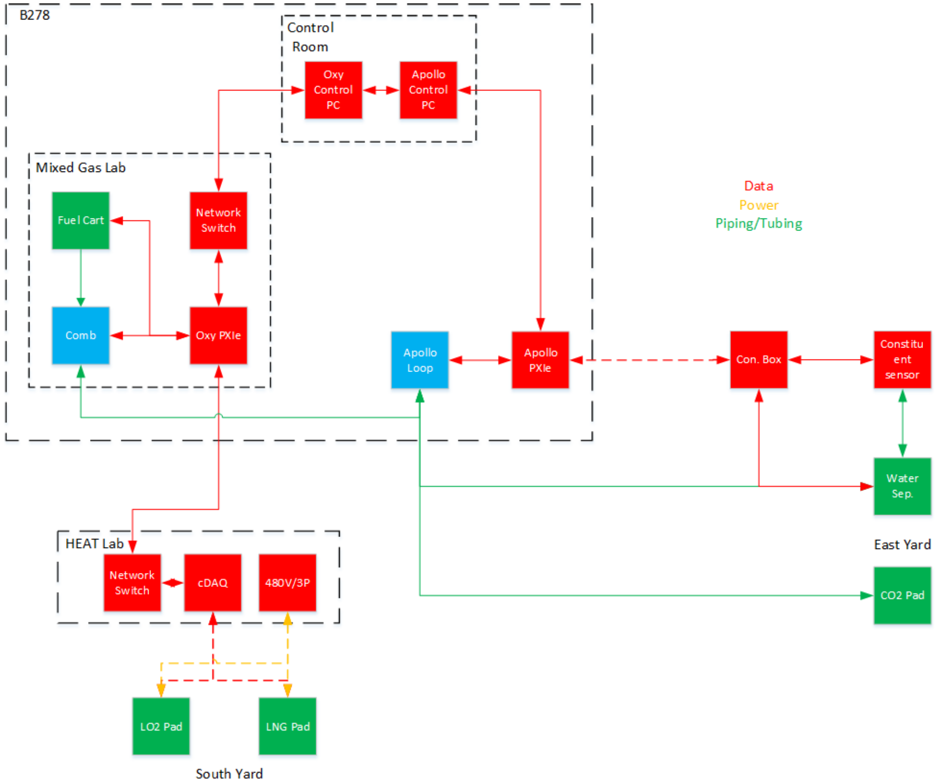
- Heater outlet to Combustor Inlet
- Fuel and Oxygen supply pads
- Fuel supply and vent lines
- Water Separator



DAQ & Instrumentation

Purchased Components:

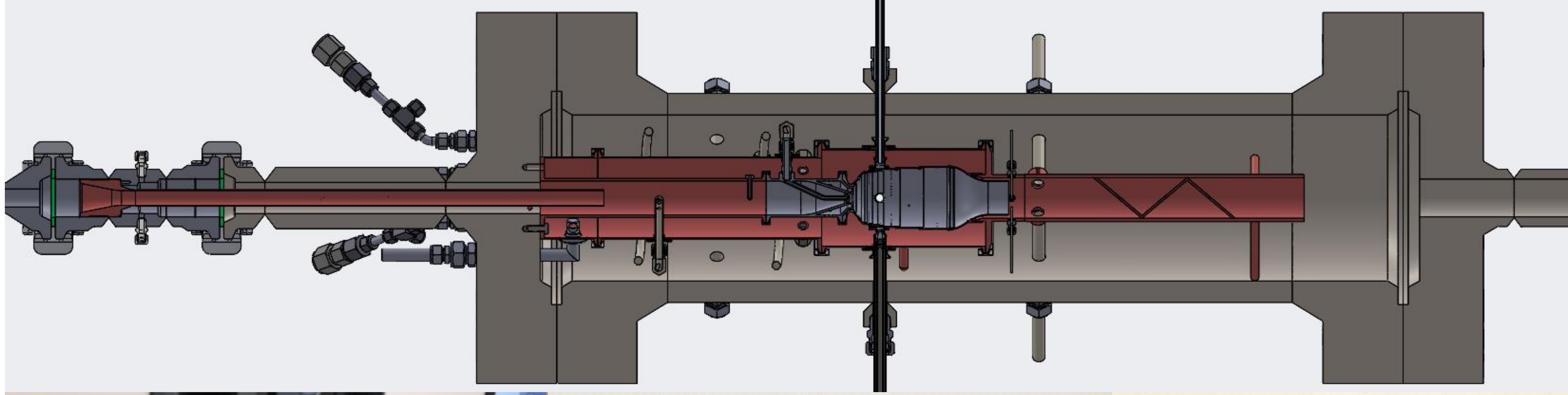
- PXIe chassis
- cDAQ
- Voltage Cards
- Amperage Cards

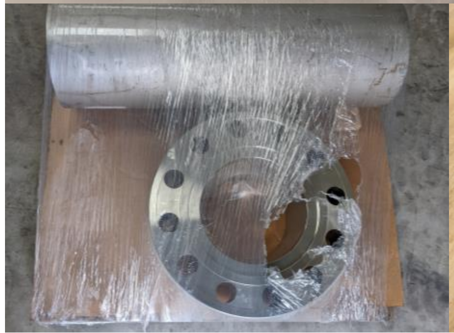


Combustor

Completed Components:

- Inlet spool
- Inlet flange
- Thermal lining tubes
- Primary flow inlet
- Fuel injector
- Combustor liner
- Exhaust mixer
- Pass-through grommets
- Casing and Exit flanges
- Thread-o-lets
- Compression fittings
- Optical probes
- Laser-ignition probe





Questions

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