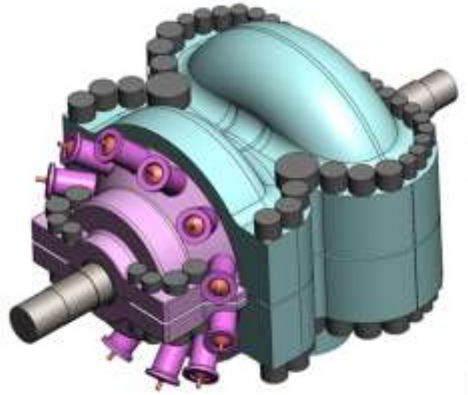
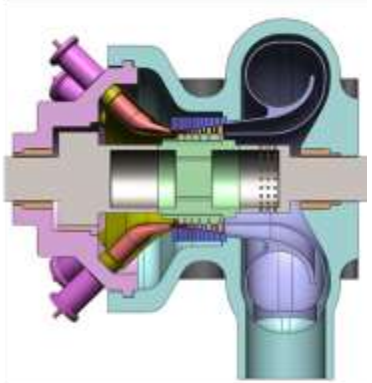
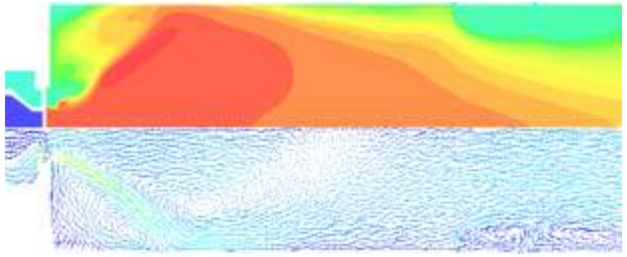
# Oxy-Fuel Combustion and Advanced Power Generation Turbines







**Timothy C. Allison, Ph.D.**

**J. Jeffrey Moore, Ph.D.**

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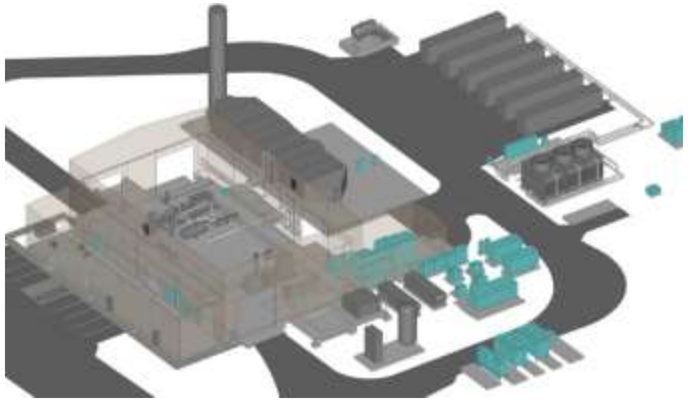
**Owen Pryor, Ph.D.**

**Southwest Research Institute**

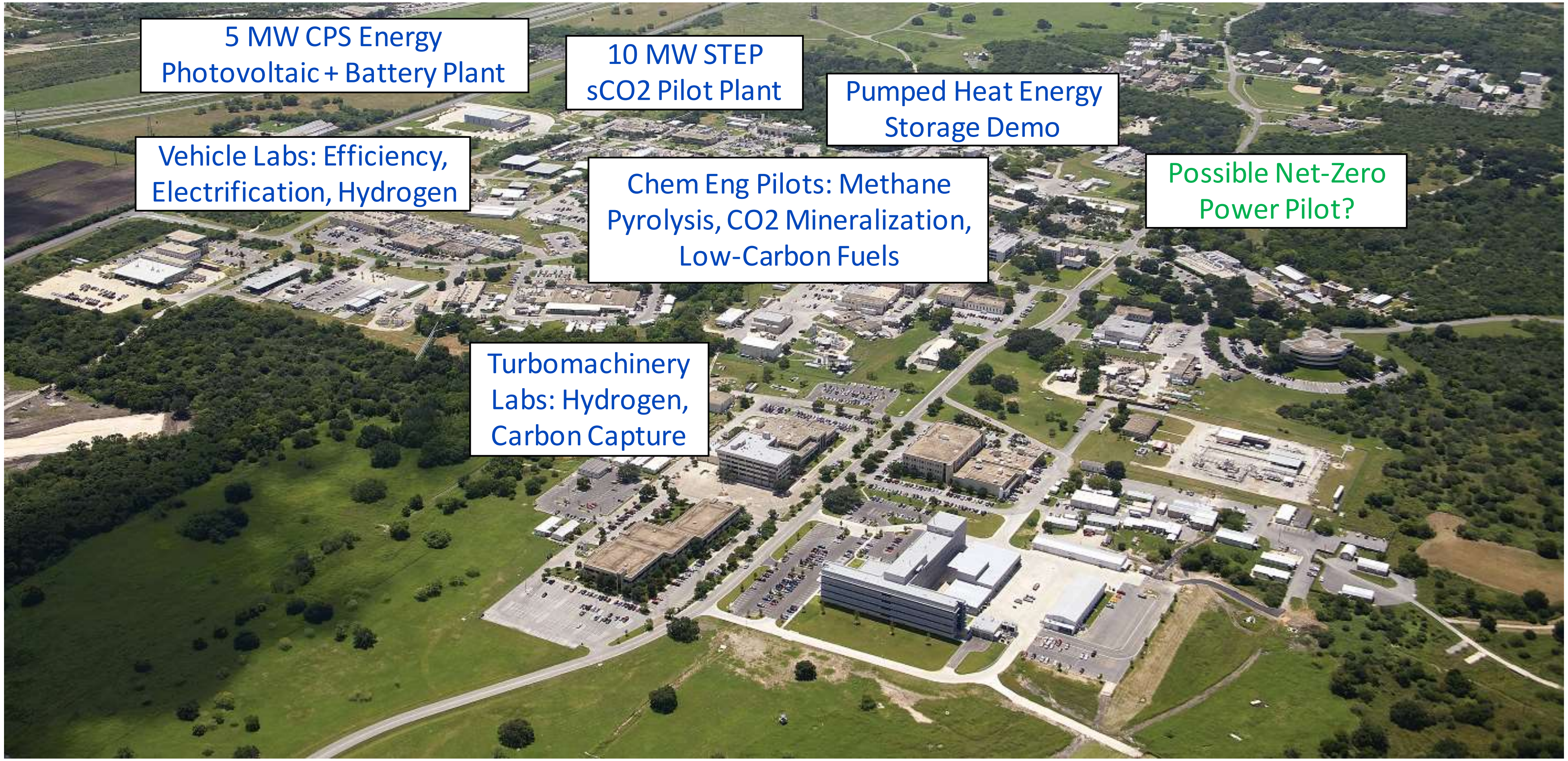


USEA Webinar

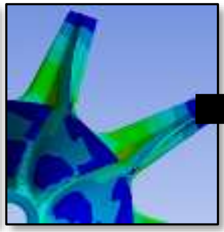
February 2, 2022

# SwRI Performs Applied Research & Development Supporting Clean Energy

- Founded in 1947
- San Antonio, Texas
- Not-for-Profit Contract R&D
- 2,800 employees
- 1,500-acre facility
- 300 labs and office buildings

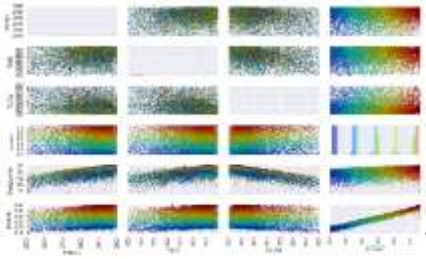


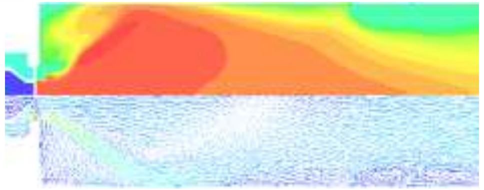
# SwRI Machinery Department

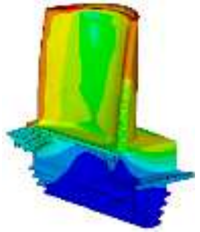



Applied Research centered around Rotating Machinery and associated systems for

- Oil & Gas
- Aviation
- Liquid Propulsion
- Power Generation

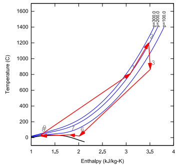


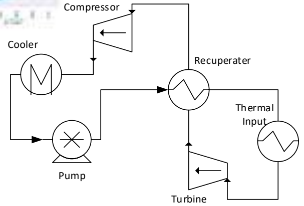


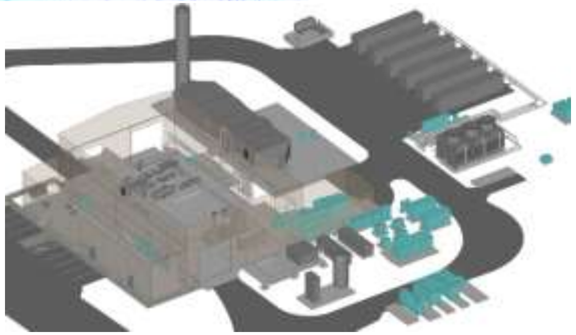


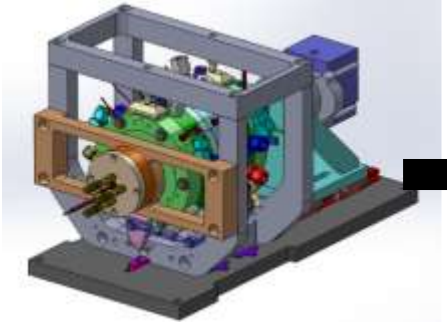
Expertise including developing technologies, prototype demonstration, and mature products and systems

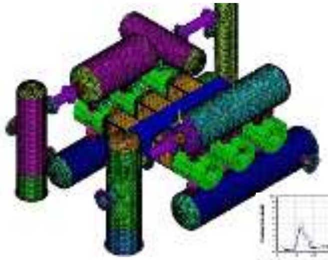
- 75 Staff
- 5 labs; open/closed-loop test facilities; powertrains up to 15 MW shaft power
- Field testing and troubleshooting
- Support OEMs in transitioning new technologies to products

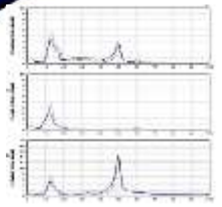




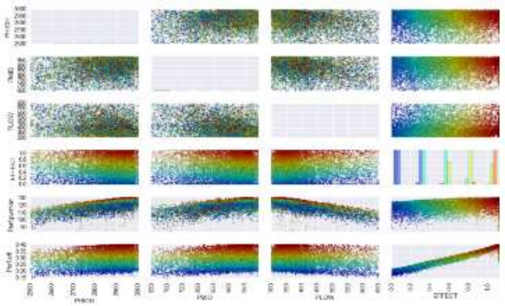


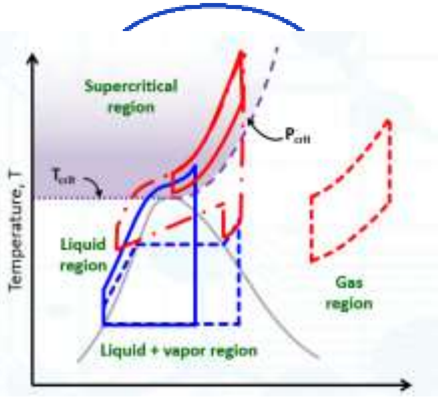


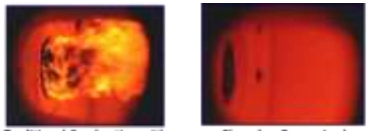


# Machinery – Advanced Power

- Advanced power cycles to improve efficiency & emissions performance
  - Long-duration energy storage
  - Supercritical CO2
  - Advanced combustion
  - Carbon capture & sequestration
  - Thermodynamic analysis & optimization, technoeconomics
- Component design and pilot-scale validation:
  - First-of-a-kind compressor, expander, combustor, heat exchanger designs
  - Up to 4000 psi, 1320 °F
  - 1, 3, and 10 MWe component test facilities
  - STEP Supercritical CO2 pilot plant

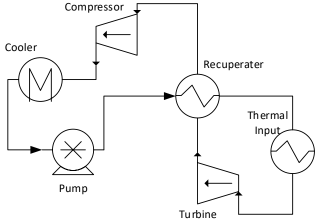


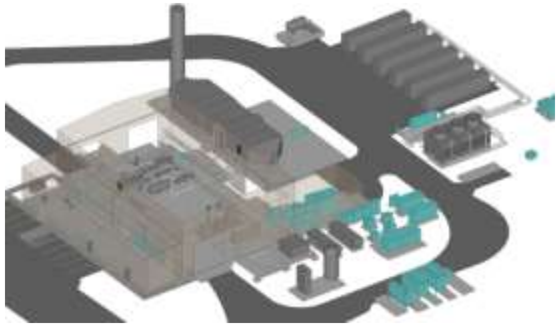


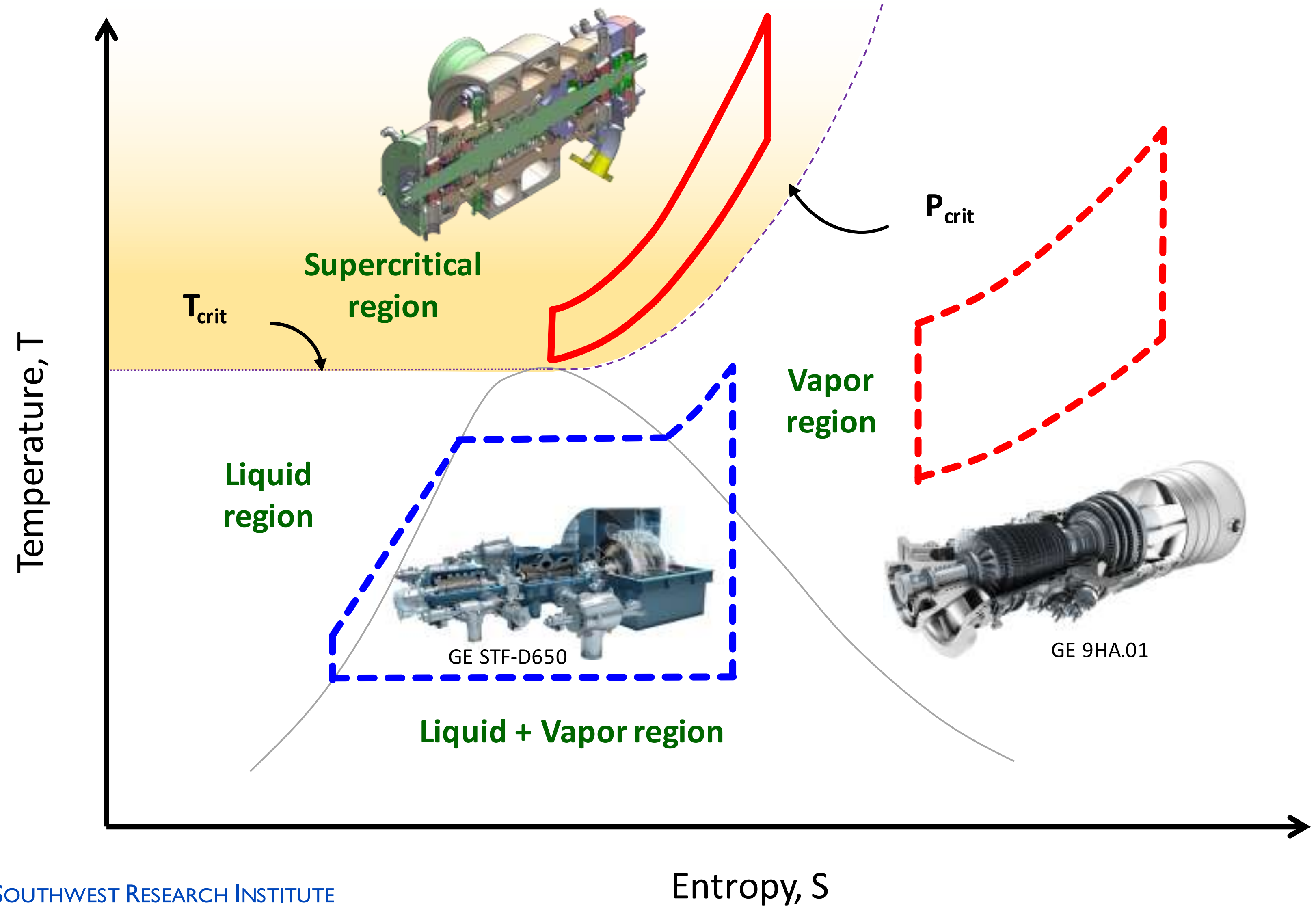
Traditional Combustion with Flame Front

Flameless Pressurized Combustion



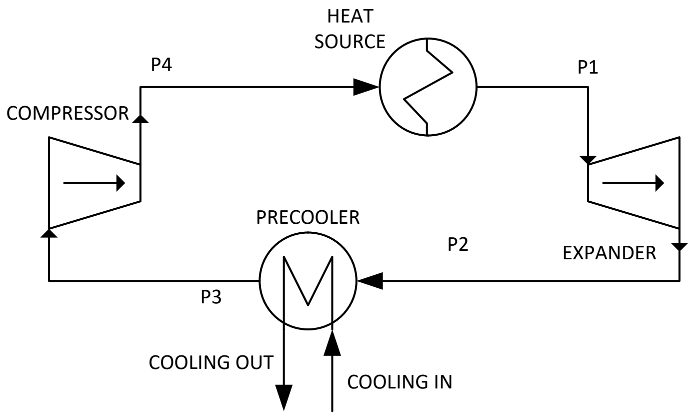



# What is a Supercritical Carbon Dioxide (sCO2) Power Cycle?

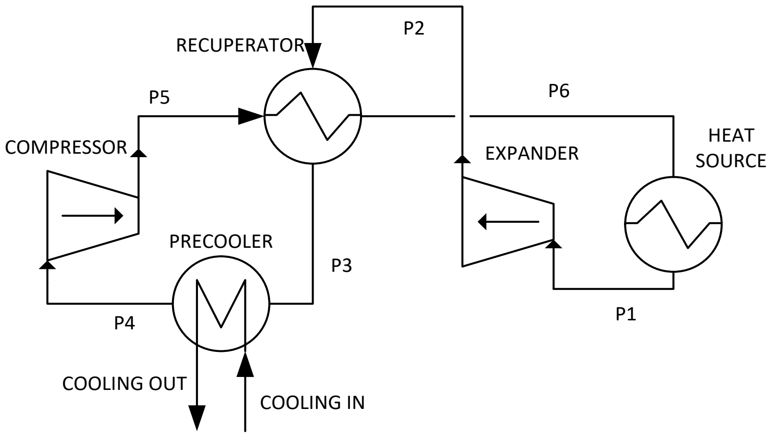



- Operates above critical Temperature and Pressure
- CO2 is a good working fluid
  - Low critical point
  - Manageable corrosion characteristics
- System design must account for real gas effects in components
- Closed cycle has minimal fluid losses, near-hermetic system

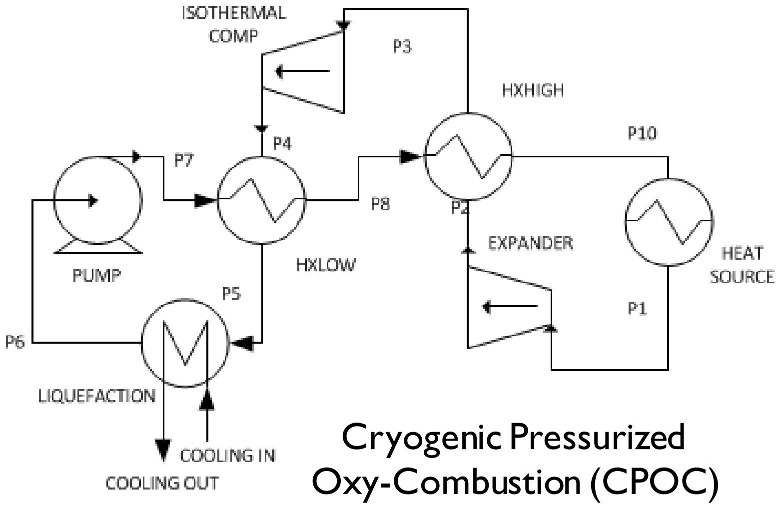
# Closed Brayton Cycle Configurations



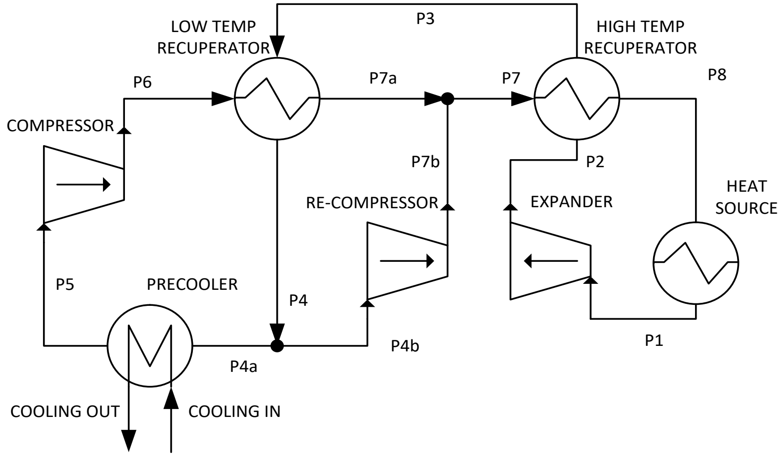

Simple Closed Brayton Power Cycle




Recuperated Closed Brayton Power Cycle



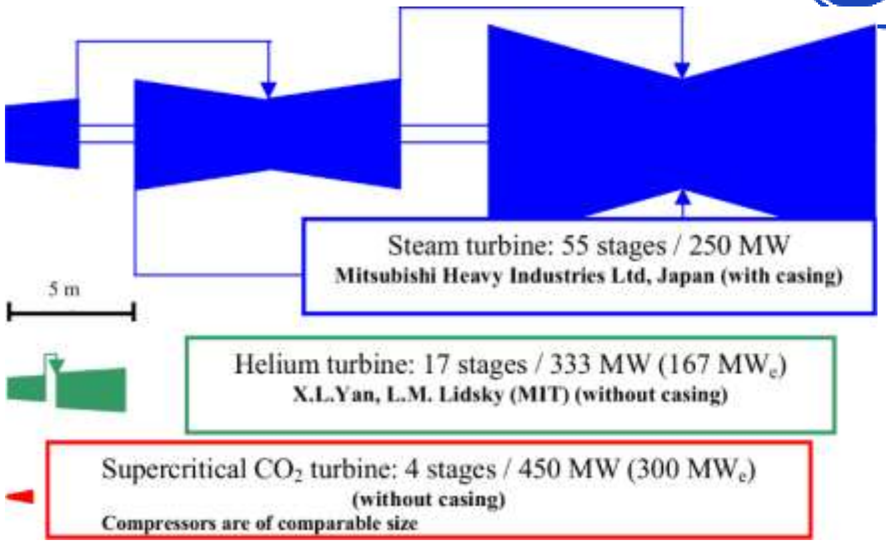

Cryogenic Pressurized
Oxy-Combustion (CPOC)

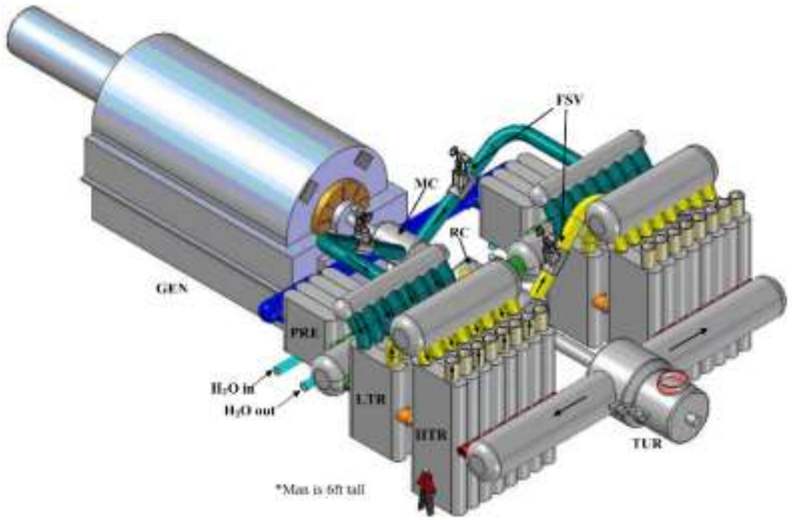



Recompression Closed Brayton Power Cycle

# Why $sCO_2$ Power Cycles?

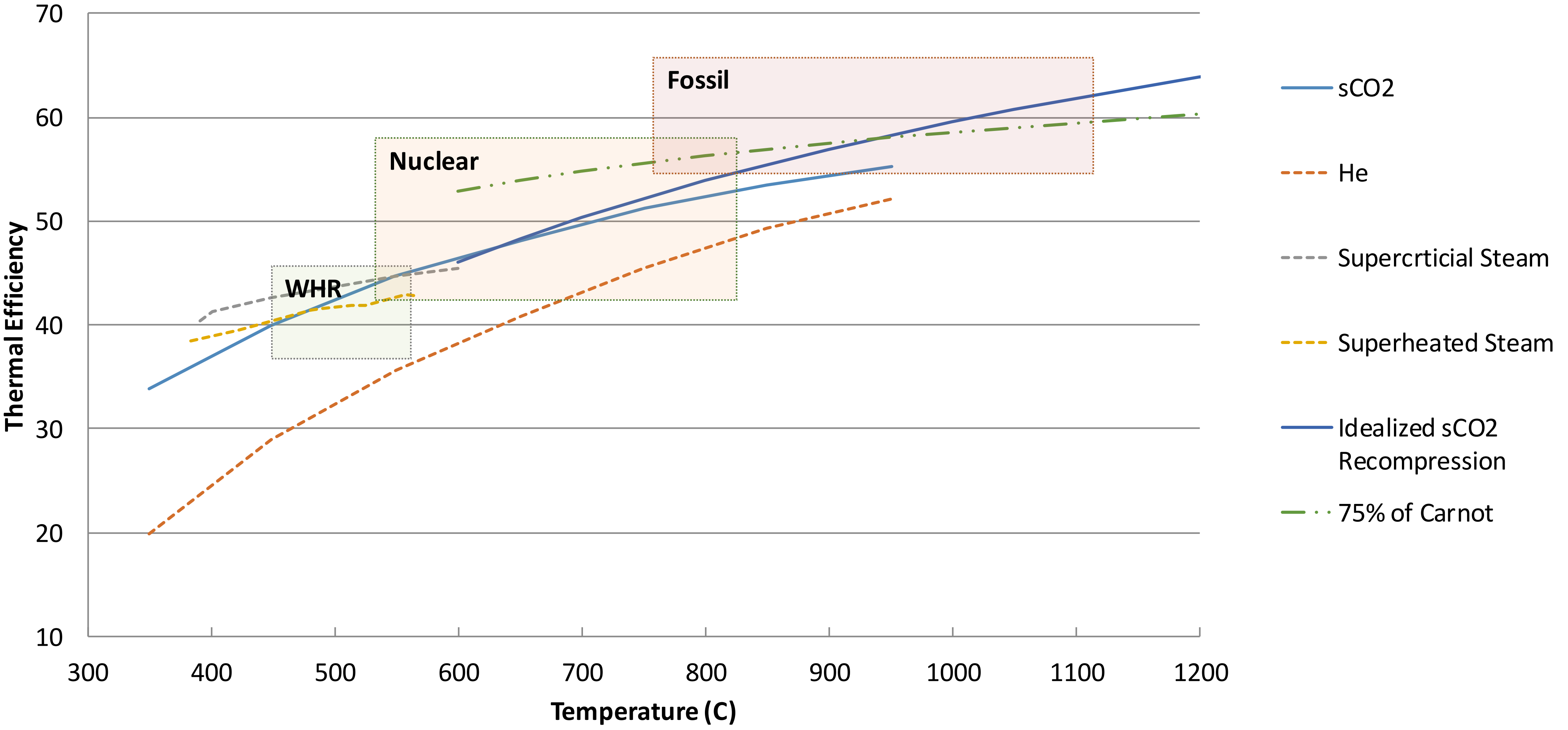
- Offer +3 to +5 percentage points over supercritical steam for indirect cycles
- High fluid densities lead to compact turbomachinery
- Efficient cycles require significant recuperation
- Compatible with dry cooling techniques




Third Generation 300 MWe S-$CO_2$ Layout from Gibba, Hejzlar, and Driscoll, MIT-GFR-037, 2006

# Representative Cycle Efficiencies




$sCO_2$, He, Supercritical Steam, and Superheated Steam are from Driscol MIT-GFR-045, 2008

# Supercritical $CO_2$ Cycle Applications

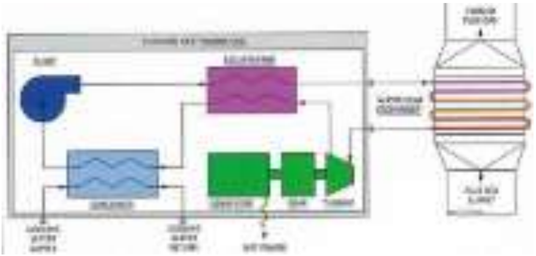
<u>Primary Power</u>
- High grade heat
- Optimized for system efficiency
- 0.3-2000 MWe

Concentrating Solar Power

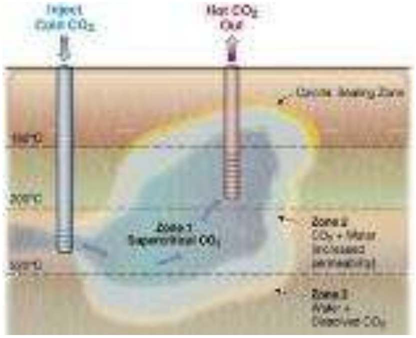
Fossil Fuel

Nuclear

<u>Bottoming Cycles</u>
- Low grade heat
- Optimized for net power
- 2-10 MWe



Waste Heat Recovery



Geothermal

# Supercritical Transformational Electric Power (STEP) Pilot Plant Test Facility

**Objectivse**:

- Advance the state of the art for high temperature $sCO_2$ systems
- Design, construct, and operate a *reconfigurable* 10 MWe $sCO_2$ Pilot Plant Test Facility

**Key Advances:**

- Turbomachinery for 715C
- 740h Primary HX & Piping @ 250 bar, 715C,
- Recuperator scale up at 600C design temperatures
- Plant Controls and Operability

**Project Team & Timeline**:

- $122M Project and Building Budget with $84M Federal Funding
- System commissioning planned for late 2021
- Project Team includes: U.S. Department of Energy (DOE NETL), Gas Technology Institute (GTI), Southwest Research Institute (SwRI), and General Electric Global Research (GE-GR)

**Joint Industry Partners Include:**


**Project Publications**:

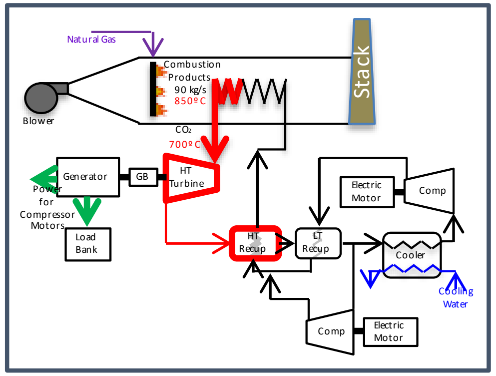
1. Marion, Kutin, McClung, Mortzheim, Ames, 2019, "The STEP 10 Mwe sCO2 Pilot Plant Demonstration," Proc. of ASME Turbo Expo 2019, Paper GT2019-91917, June 17–21, 2019, Phoenix, AZ, USA.
2. Tang, McClung, Hofer, Huang, 2019, "transient Modeling of 10 MW supercritical CO2 Brayton Power Cycles using Numerical Propulsion System Simulation (NPSS)," Proc. of ASME Turbo Expo 2019, Paper GT2019-91443, June 17–21, 2019, Phoenix, AZ, USA.
3. Huang, Tang, McClung, 2018, "Steady State and Transient Modeling for the 10 MWe SCO2 Test Facility Program," Proc. 6th Intl. Symp. – Supercritical CO2 Power Cycles, March 27-29, Pittsburgh, PA.

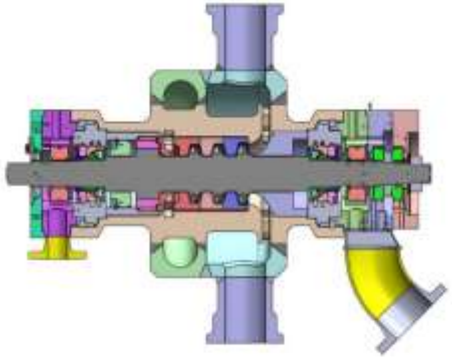
# Progressing Technology to Pilot Scale Demonstration

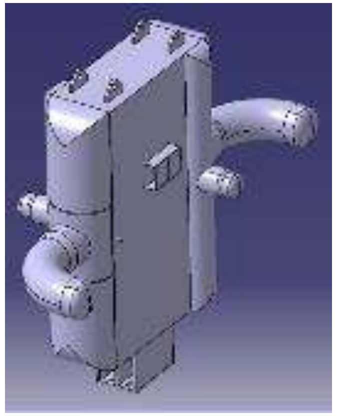
STEP DEMO

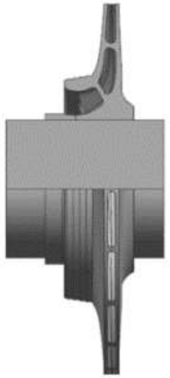
SwRI

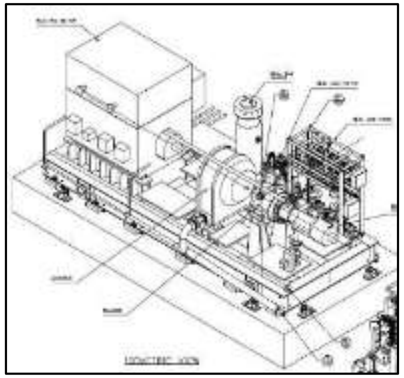
## Individual Cycle and Component Development



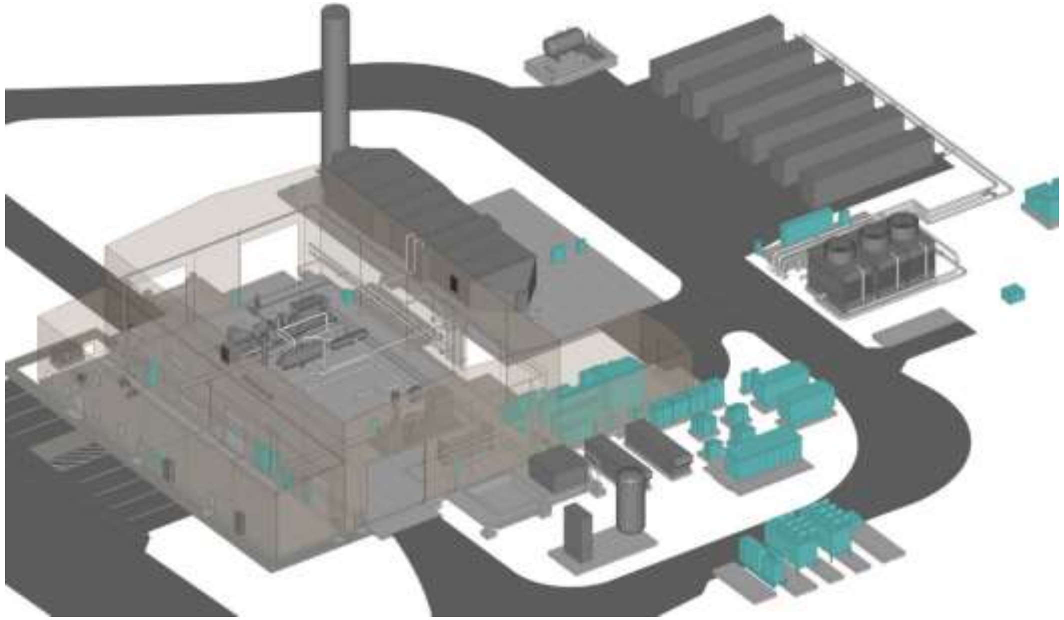






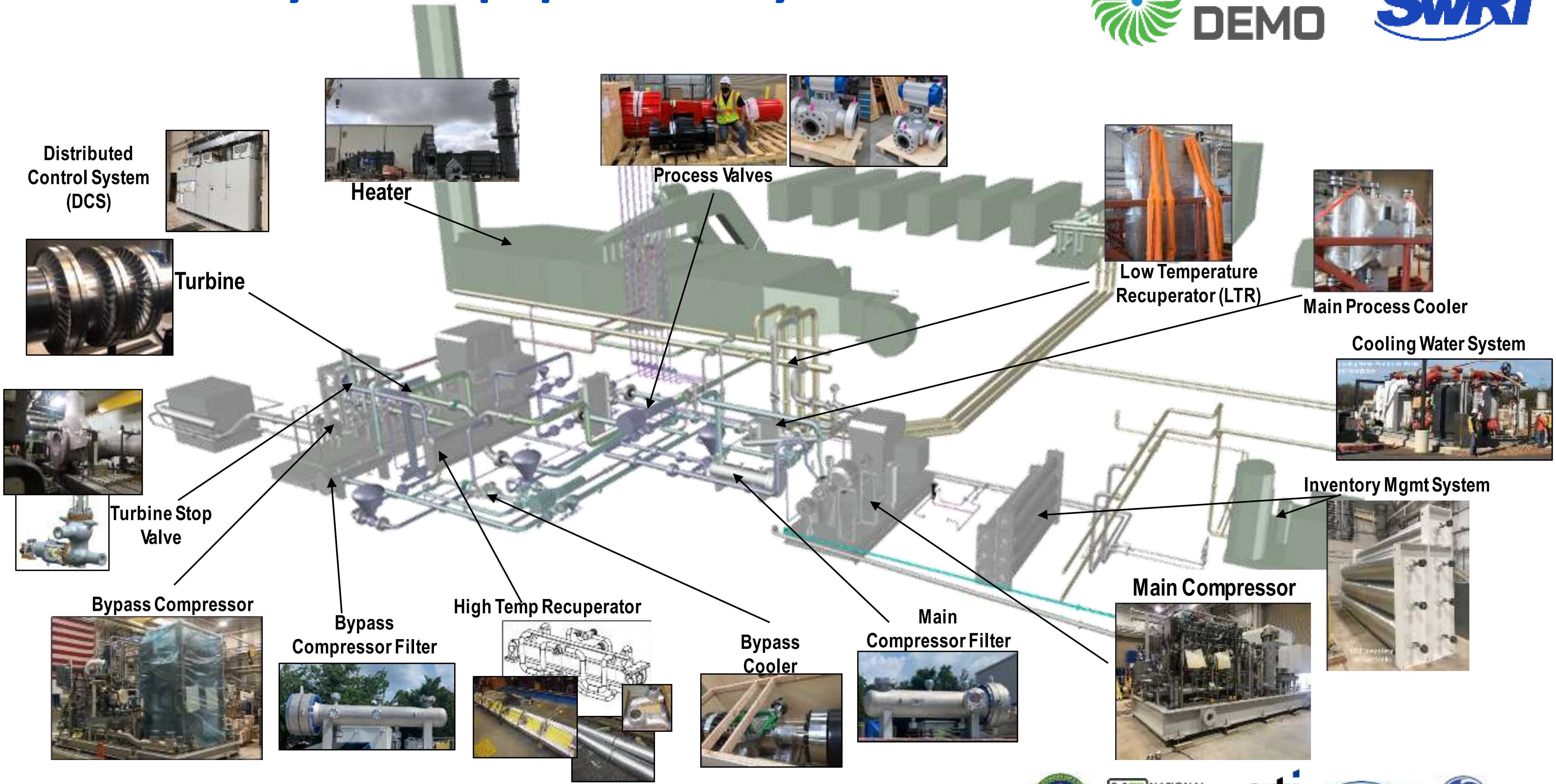
Leveraging \$60 million in DOE investments into $sCO_2$ technology development

## STEP Integrated Pilot Scale System Demonstration

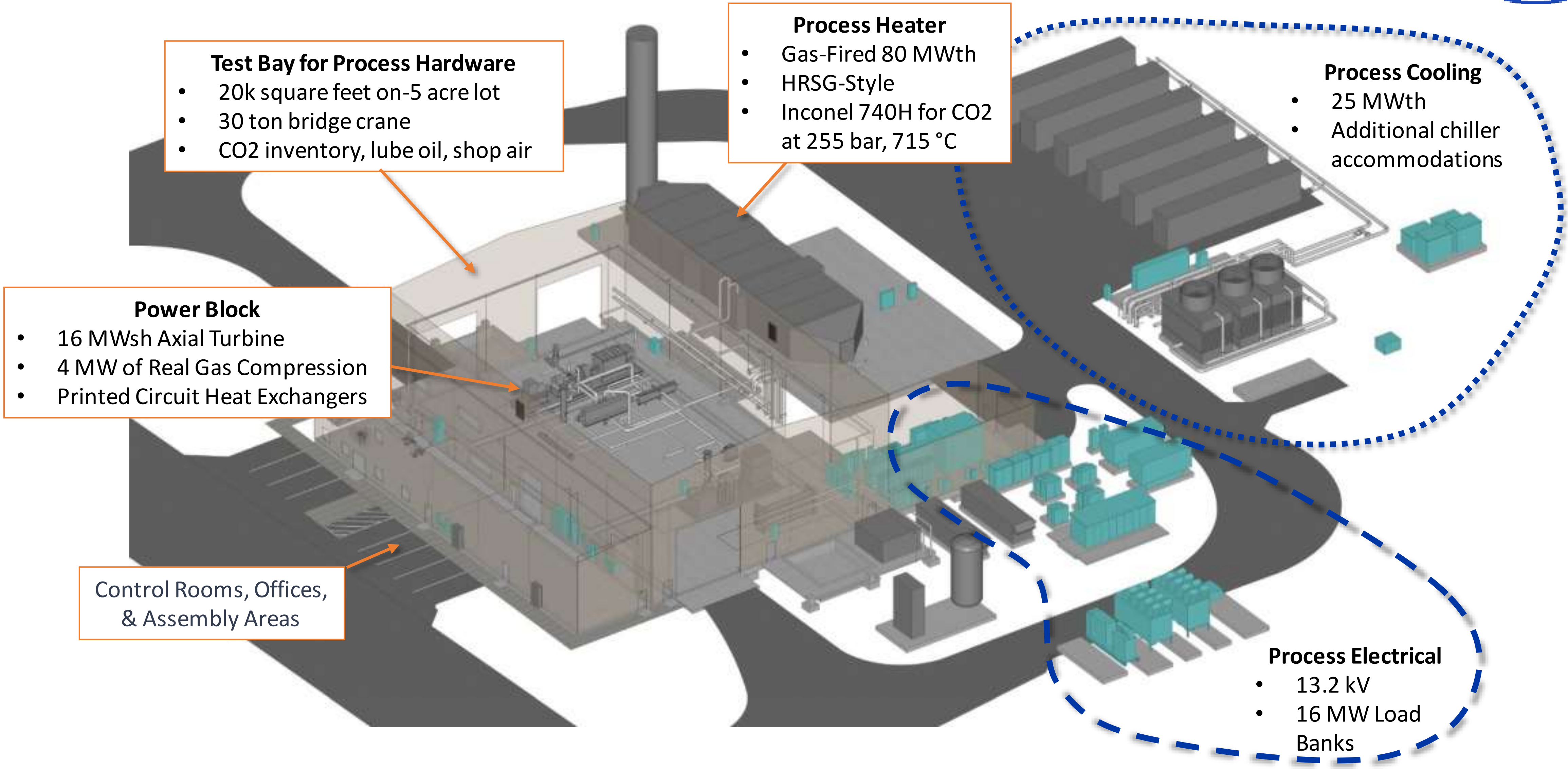


- Demonstrate $sCO_2$ system operability
- Verify component performance
- Show the potential for lower cost of electricity and high thermodynamic efficiency

# STEP Facility and Equipment Layout

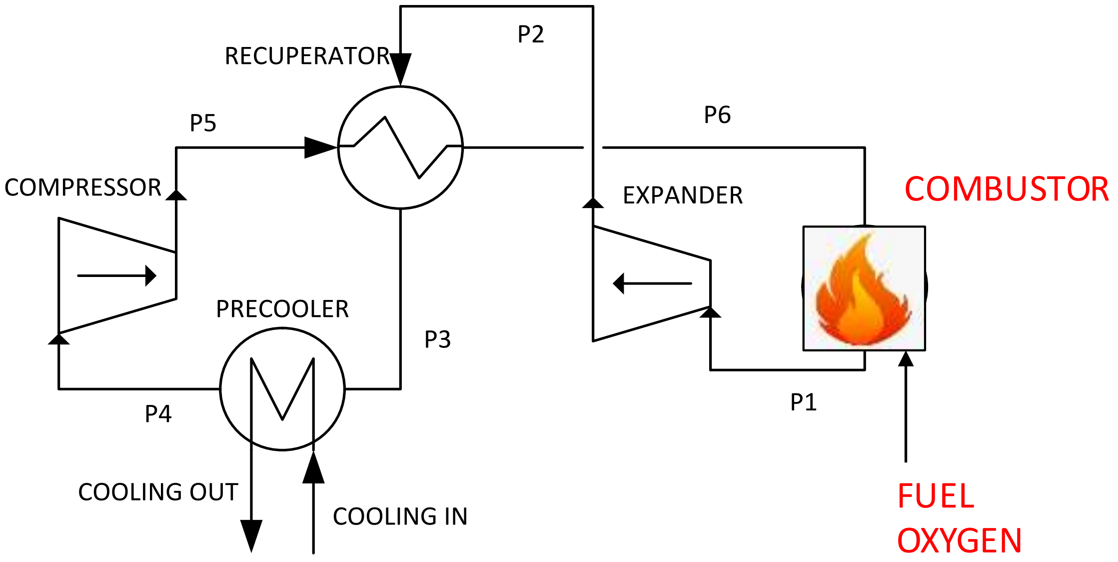


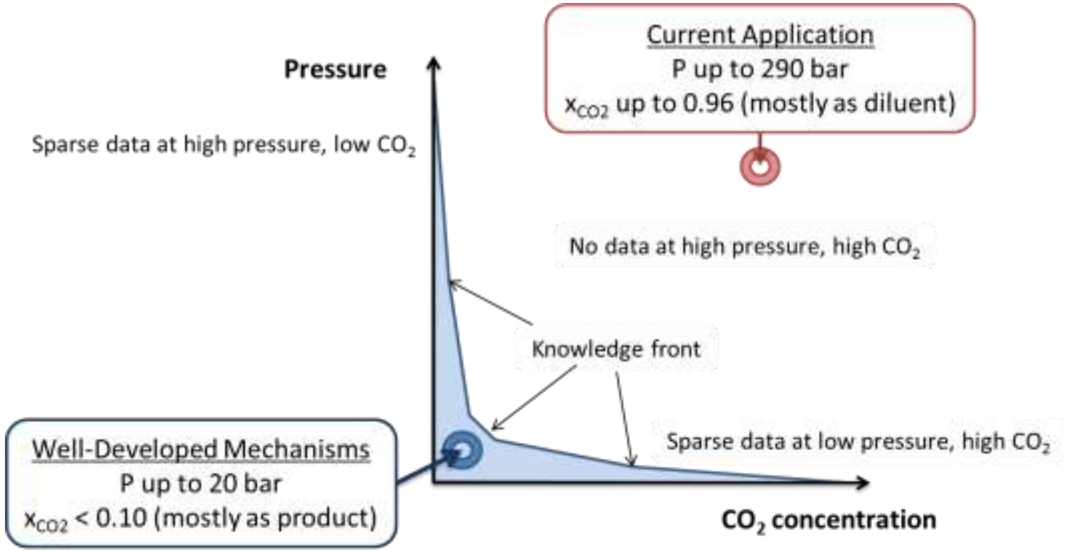
# Flexible Test Facility Capabilities



# Introduction to sCO2 Oxy-Combustion

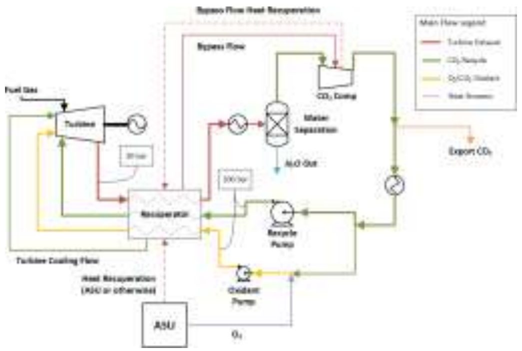
- Direct combustion for heat addition creates CO2, water, other byproducts
- Favorable emissions
  - Inherent carbon capture
  - No Nitrogen, no Nox
- High efficiency
- Several "new" components
  - Combustor, cooled turbine



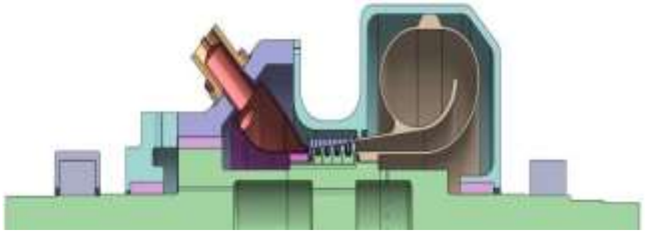



# Development of Oxy-Fuel Combustion Turbines with $CO_2$ Dilution for Supercritical Carbon Dioxide Based Power Cycles

## University Turbine Systems Research Project Review Meeting




**Jeff Moore, Ph.D.**
Institute Engineer
Southwest Research Institute

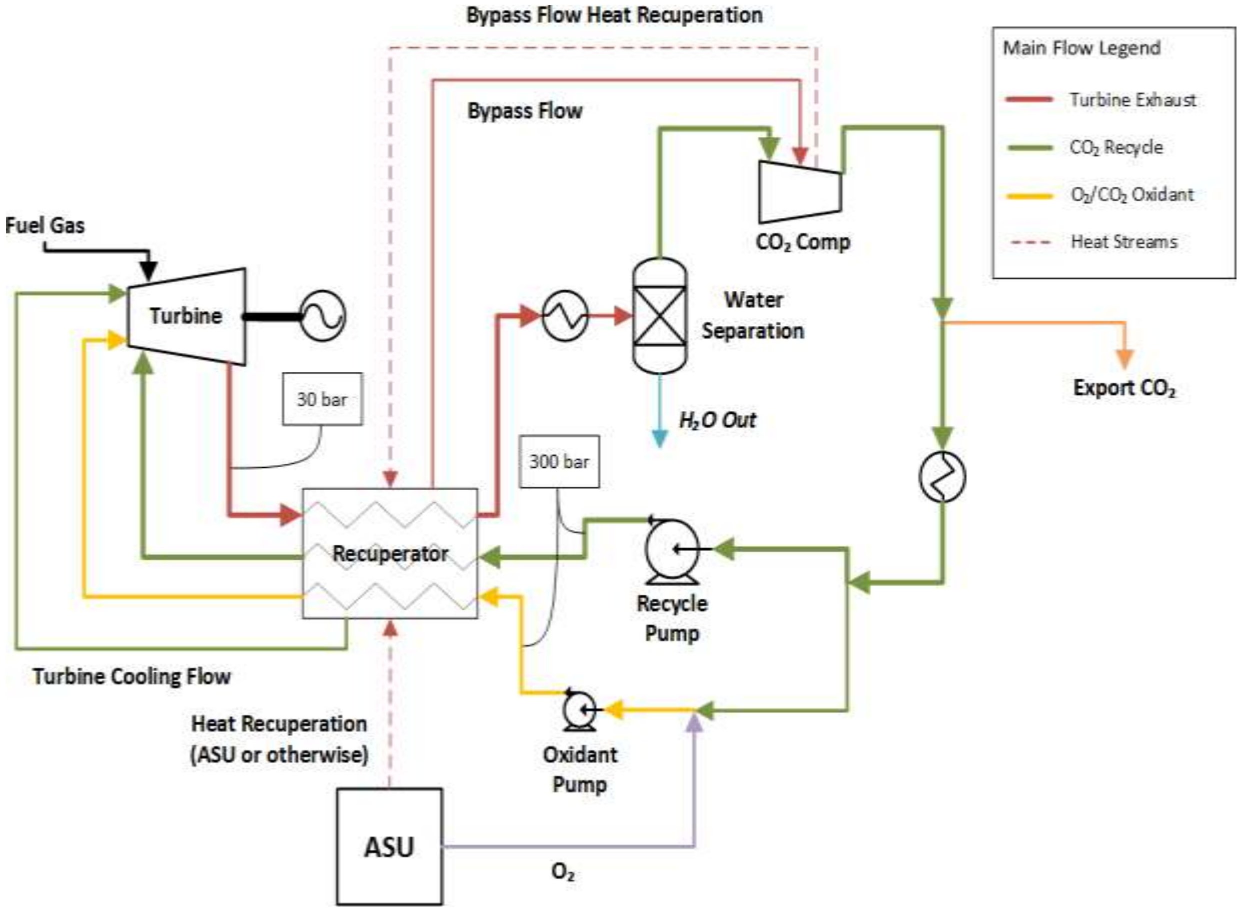




**DE-FE0031620**
**SwRI Project 23916**


**NETL PM: Seth Lawson**
2019 UTSR Project Review Meeting
Nov. 5-7, 2019

# Project Objectives

- Develop a conceptual design for a $sCO_2$, coal syngas or natural gas-fired oxy-fuel turbine in the 150-300 MWe size range capable of 1,200°C turbine inlet temperature at 30 MPa and exhaust temperatures in the 725-775°C range.
- Significantly improve the state-of-the-art for thermal efficiency and results in a high-pressure stream of $CO_2$ simplifying carbon capture, making the power plant emission-free.



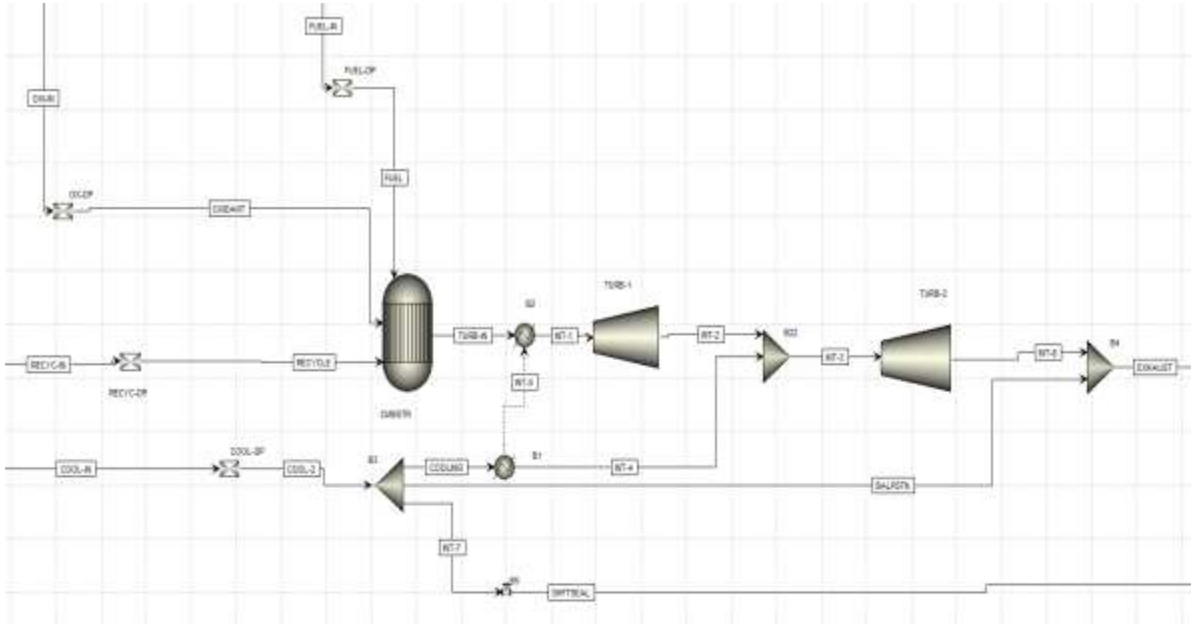
# Phase I: Technical Approach

- Develop a conceptual oxy-fuel $sCO_2$ combustion turbine design: SwRI and GE (Aero, mechanical, thermal management), Air Liquide (combustor), EPRI (materials), and Georgia Tech (combustion kinetics).
- Develop a thermodynamic cycle analysis (heat, mass, and energy balance) for a $sCO_2$ semi-closed recuperated Brayton cycle based on natural gas, as the fuel and the proposed $sCO_2$ turbine: 8 Rivers.
- Consistent with the conceptual design and cycle analysis, develop nominal engine component boundary conditions in terms of pressures, temperatures, mass flows, heat flux etc.: 8 Rivers, GE and SwRI.

# Aspen Cycle Model

| | COOL-IN | COOLING | FUEL-IN | FUEL | OXI-IN | OXIDANT | RECYC-IN | RECYCLE | TURB-IN | EXHAUST |
|---|---|---|---|---|---|---|---|---|---|---|
| Substream: MIXED | | | | | | | | | | |
| Mole Flow kmol/hr | | | | | | | | | | |
| CH4 | 0 | 0 | 2436.61 | 2436.61 | 0 | 0 | 0 | 0 | 2.58E-22 | 2.58E-22 |
| O2 | 40.7438 | 40.7438 | 0 | 0 | 5024.019 | 5024.019 | 366.6942 | 366.6942 | 517.4953 | 558.2391 |
| AR | 51.58562 | 51.58562 | 0 | 0 | 190.9455 | 190.9455 | 464.2706 | 464.2706 | 655.2161 | 706.8017 |
| CO | 0.010801 | 0.010801 | 0 | 0 | 0.034832 | 0.034832 | 0.097208 | 0.097208 | 0.137188 | 0.147989 |
| H2 | 0.000336 | 0.000336 | 0 | 0 | 0.001084 | 0.001084 | 0.003025 | 0.003025 | 0.004269 | 0.004605 |
| CO2 | 5106.204 | 5106.204 | 0 | 0 | 16467.09 | 16467.09 | 45955.83 | 45955.83 | 64859.53 | 69965.74 |
| H2O | 3.286727 | 3.286727 | 0 | 0 | 10.59943 | 10.59943 | 29.58054 | 29.58054 | 4913.4 | 4916.687 |
| Mass Flow kg/hr | | | | | | | | | | |
| CH4 | 0 | 0 | 39089.95 | 39089.95 | 0 | 0 | 0 | 0 | 4.14E-21 | 4.14E-21 |
| O2 | 1303.753 | 1303.753 | 0 | 0 | 160763 | 160763 | 11733.77 | 11733.77 | 16559.23 | 17862.98 |
| AR | 2060.742 | 2060.742 | 0 | 0 | 7627.891 | 7627.891 | 18546.68 | 18546.68 | 26174.57 | 28235.32 |
| CO | 0.302536 | 0.302536 | 0 | 0 | 0.975654 | 0.975654 | 2.722823 | 2.722823 | 3.8427 | 4.145236 |
| H2 | 0.000678 | 0.000678 | 0 | 0 | 0.002185 | 0.002185 | 0.006098 | 0.006098 | 0.008606 | 0.009284 |
| CO2 | 224723 | 224723 | 0 | 0 | 724714 | 724714 | 2022510 | 2022510 | 2854460 | 3079180 |
| H2O | 59.21131 | 59.21131 | 0 | 0 | 190.9517 | 190.9517 | 532.9018 | 532.9018 | 88516.29 | 88575.5 |
| Total Flow kmol/hr | 5201.831 | 5201.831 | 2436.61 | 2436.61 | 21692.69 | 21692.69 | 46816.48 | 46816.48 | 70945.79 | 76147.62 |
| Total Flow kg/hr | 228147 | 228147 | 39089.95 | 39089.95 | 893296 | 893296 | 2053320 | 2053320 | 2985710 | 3213860 |
| Total Flow cum/hr | 1043.836 | 1073.55 | 226.2845 | 231.2627 | 6348.024 | 6538.998 | 13745.19 | 14156.04 | 30544.29 | 223808 |
| Temperature C | 430 | 429.5408 | 72.06623 | 71.4434 | 739 | 739.2248 | 739 | 739.1531 | 1200.009 | 778.3606 |
| Pressure bar | 316.5 | 306.5 | 315 | 305 | 315 | 305 | 315 | 305 | 305 | 30 |

- Current cycle thermal efficiency is 58%, which includes the air separation unit (ASU) and on an low heating value (LHV) basis.

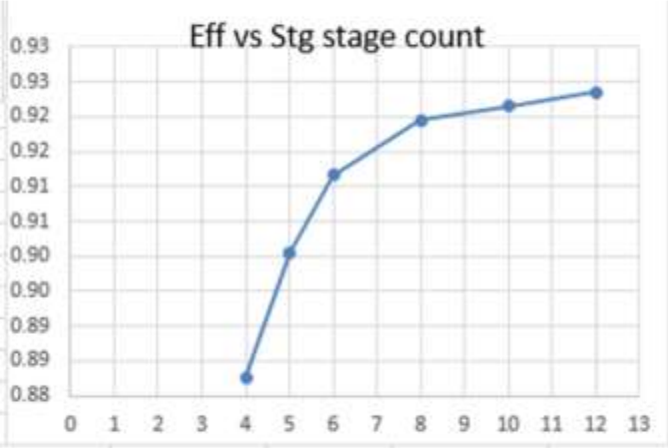



- Turbine Inlet: 305 bar @ 1,200ºC
- Turbine Exhaust: 30 bar
- Turbine Power: ~450 $Mw_{mech}$ (300 MWe Cycle) @ 90% ηs
- Cooling flow supplied to the turbine @ 400ºC

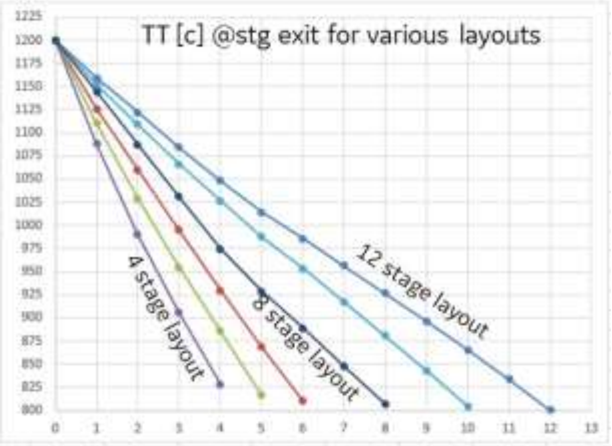
# Preliminary Turbine Sizing

| | Single Flow Turbine | | | | | | Double/Split Flow Turbine |
|---|---|---|---|---|---|---|---|
| Stage-Count | 4-Stage | 5-Stage | 6-Stage | 8-Stage | 10-Stage | 12-Stage | 12-Stage |
| Aero Hub Diameter (Inches) | 58 | 52 | 47 | 40.25 | 37 | 34 | 34.5 |
| Shaft Total-Total Efficiency | 88.3 | 90 | 91.1 | 92 | 92.1 | 92.3 | 92.1 |
| Blade-count/Stage | 142 | 142 | 142 | 142 | 96 | 96 | 140 |
| Turbine Length (Inches) | 21 | 22 | 24 | 35 | 40 | 43 | 40 |

More stages result in higher efficiency but more blades require more cooling flow







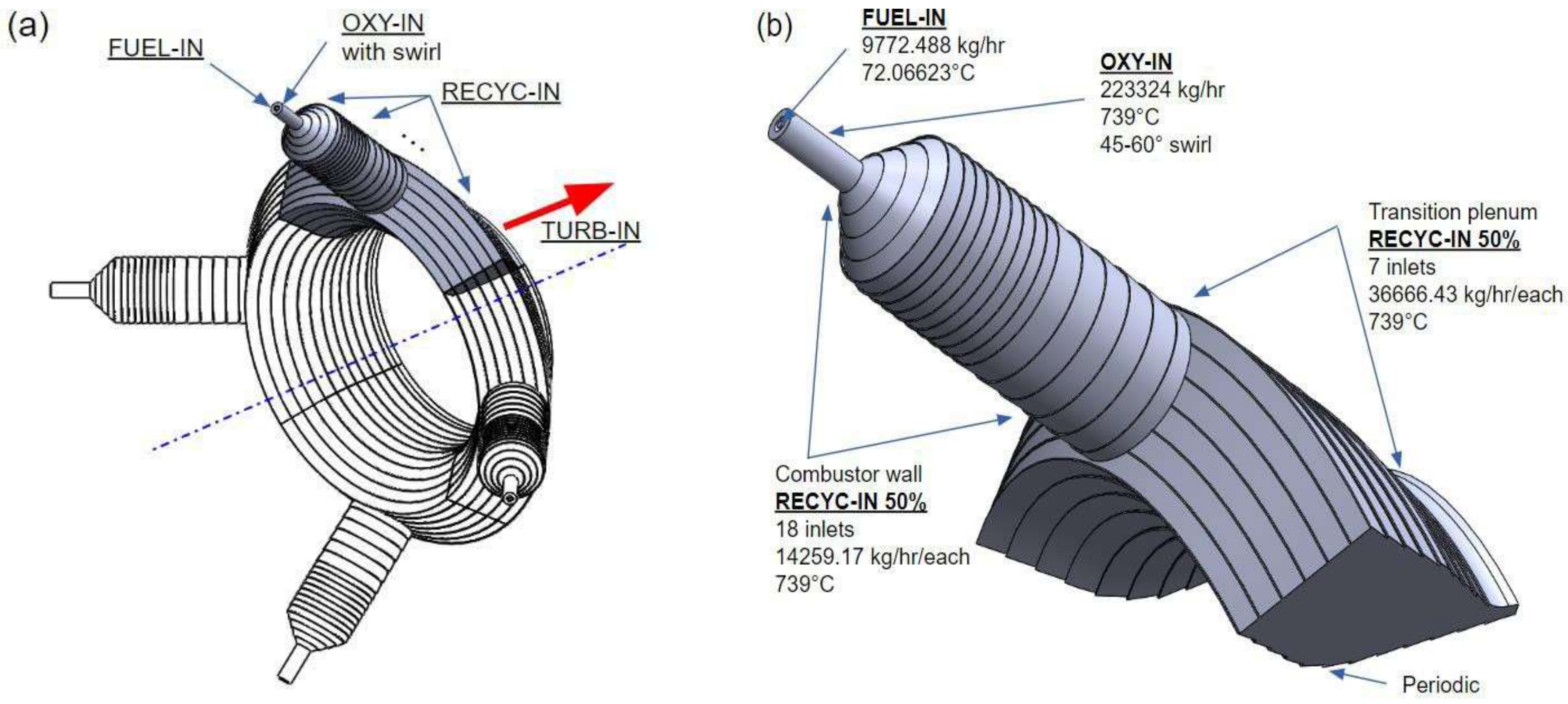
# Single vs Double Flow Turbine Layout

- Optimum number of stages selected for each configuration
- Includes effects of shaft seals
- Single flow has better aero efficiency and lower seal leakage
  - Less leakage for seals that inject cooling flow into rotor
- 5 stage single flow design showed optimum performance

| FLAVOR | STAGES | COOLING | SEAL LEAKAGE | TOTAL | AERO | RELATIVE EFFICIENCY CHANGE |
|---|---|---|---|---|---|---|
| | # | % of Recycle Flow | | | % | % |
| SINGLE | 4 | 4.16 | 3.40 | 7.56 | 88.3 | 1.19 |
| SINGLE | 5 | 5.55 | 3.40 | 8.95 | 90.0 | 1.92 |
| SINGLE | 6 | 7.47 | 3.40 | 10.87 | 91.1 | 1.69 |
| SINGLE | 8 | 11.20 | 3.40 | 14.60 | 92.0 | 0.00 |
| SINGLE | 10 | 15.86 | 3.40 | 19.26 | 92.1 | -3.13 |
| DOUBLE | 8 | 8.00 | 7.50 | 14.30 | 89.8 | -1.99 |

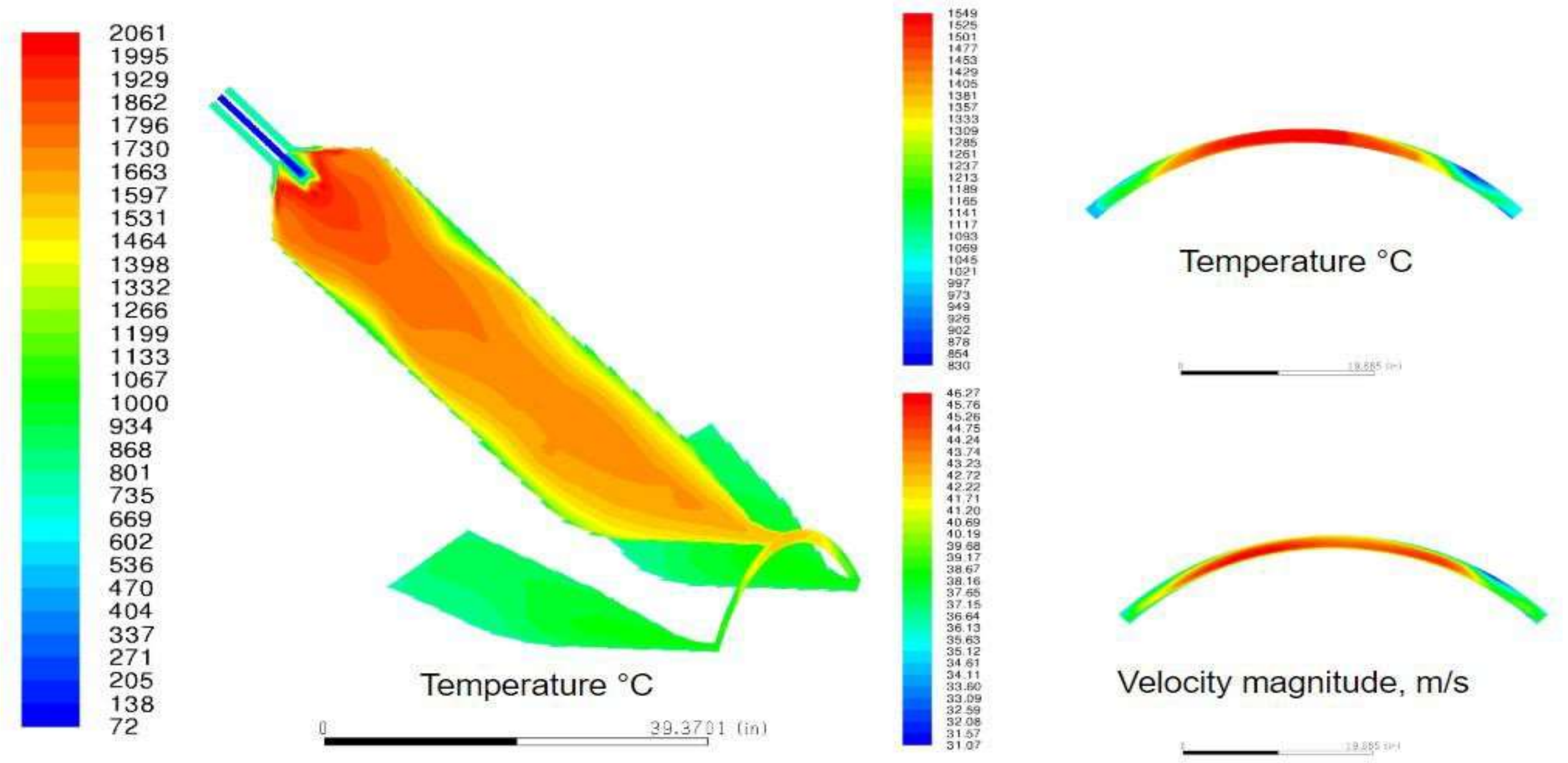
# Oxy-Fuel Combustor Concept

**ISO view of conceptual combustor geometry for straight through turbine design with 4 combustor cans, and 3D CFD fluid volume and boundary conditions**

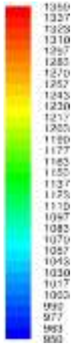
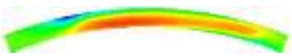
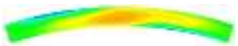
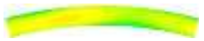


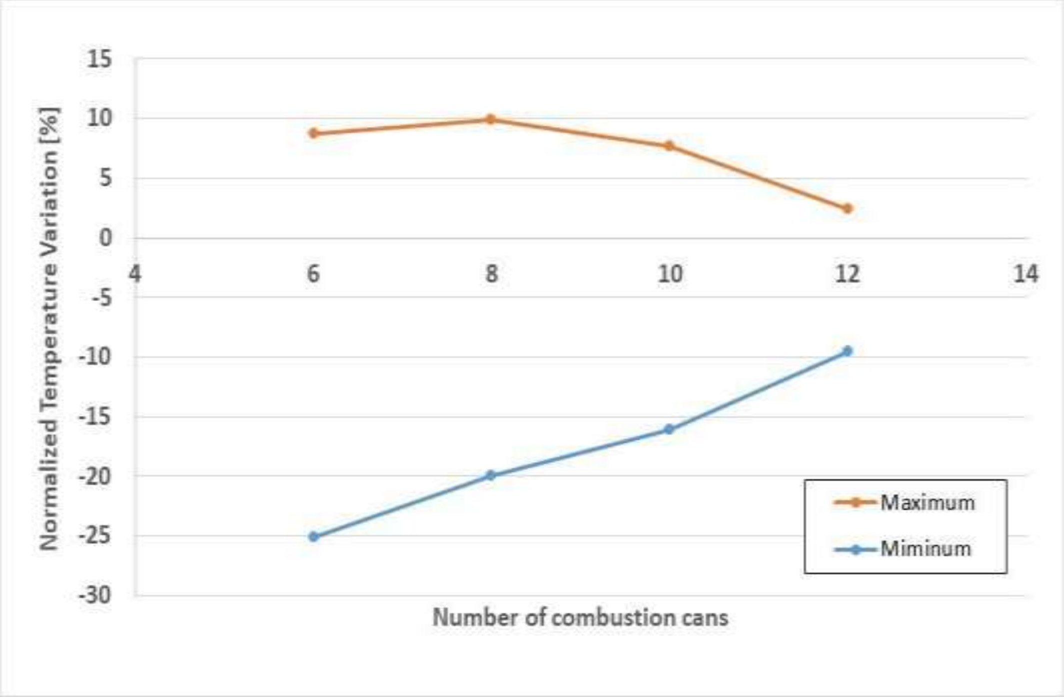
# Oxy-Fuel Combustor Concept

- **3D CFD results (case 303): Temperature profile in degree C, and Velocity magnitude [m/s]**
- **Excessive temperature and velocity variation at nozzle entrance**



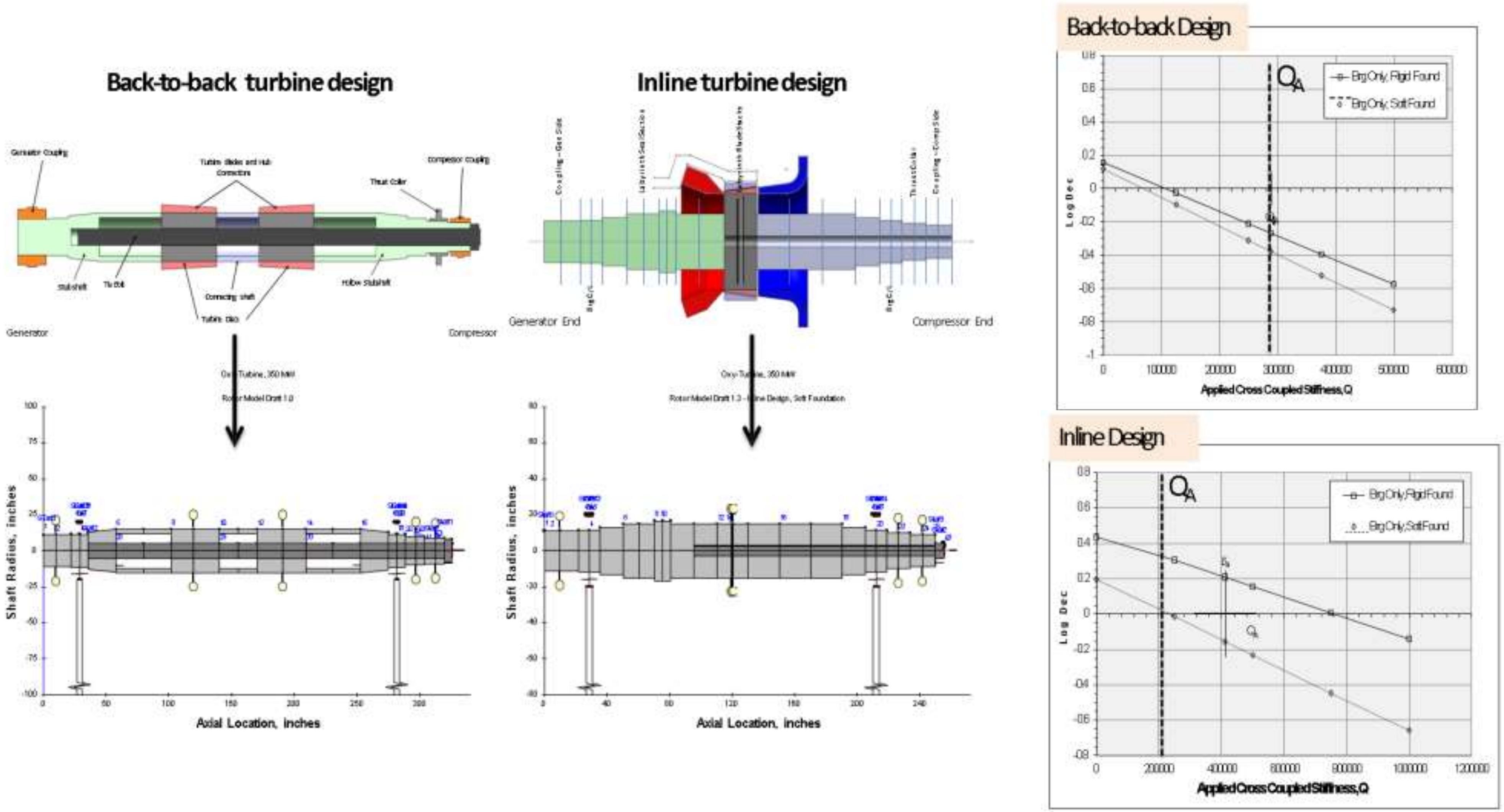
# Oxy-Fuel Combustor Concept

| | | 8 combustion cans | 10 combustion cans | 12 combustion cans |
|---|---|---|---|---|
| Velocity [m/s] profile |  |  |  |  |
| Temperature [°C] profile |  |  |  |  |



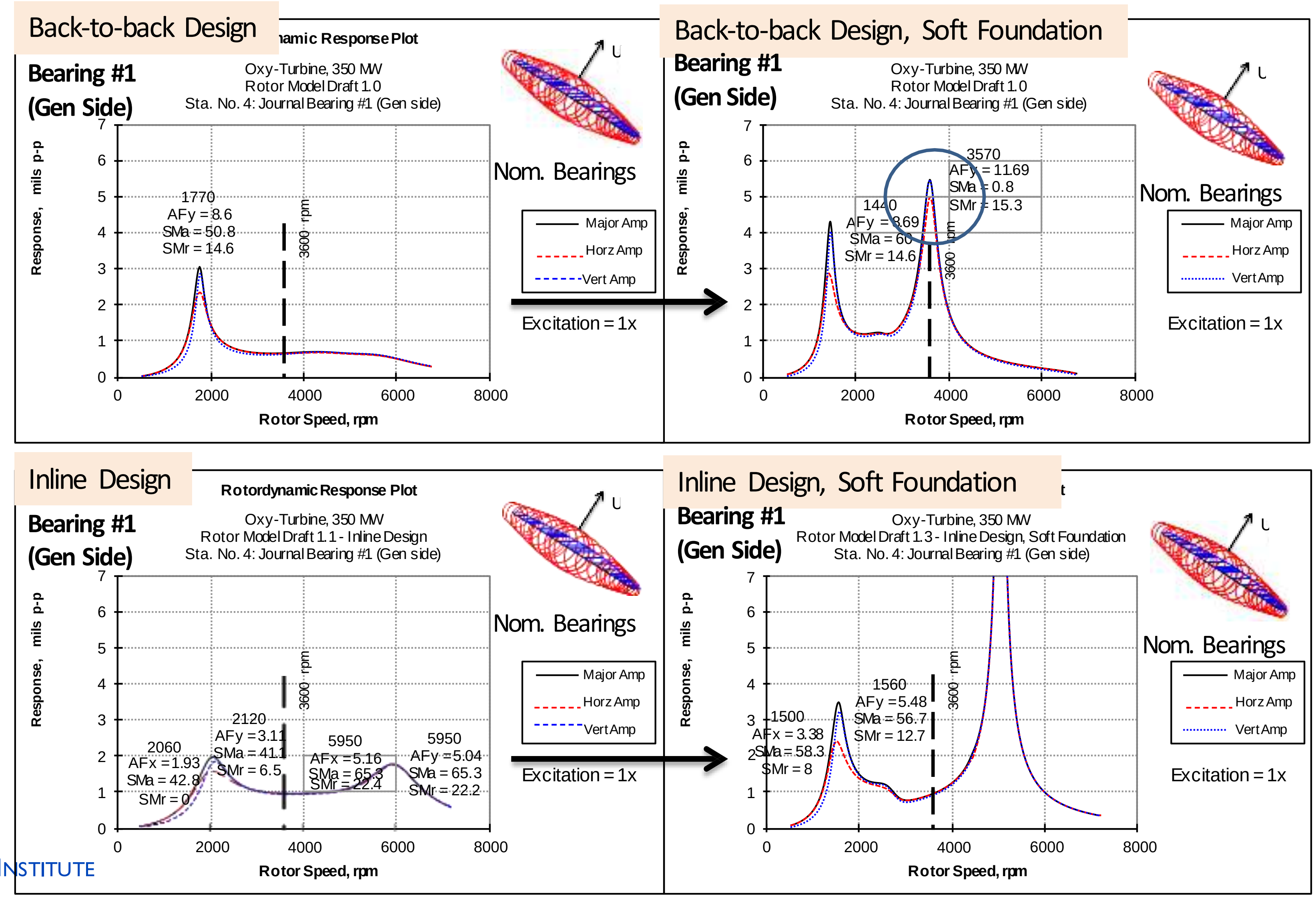
# Rotordynamic Modeling

## Comparison of Back-to-Back and Inline Turbine Design



# Rotordynamic Modeling

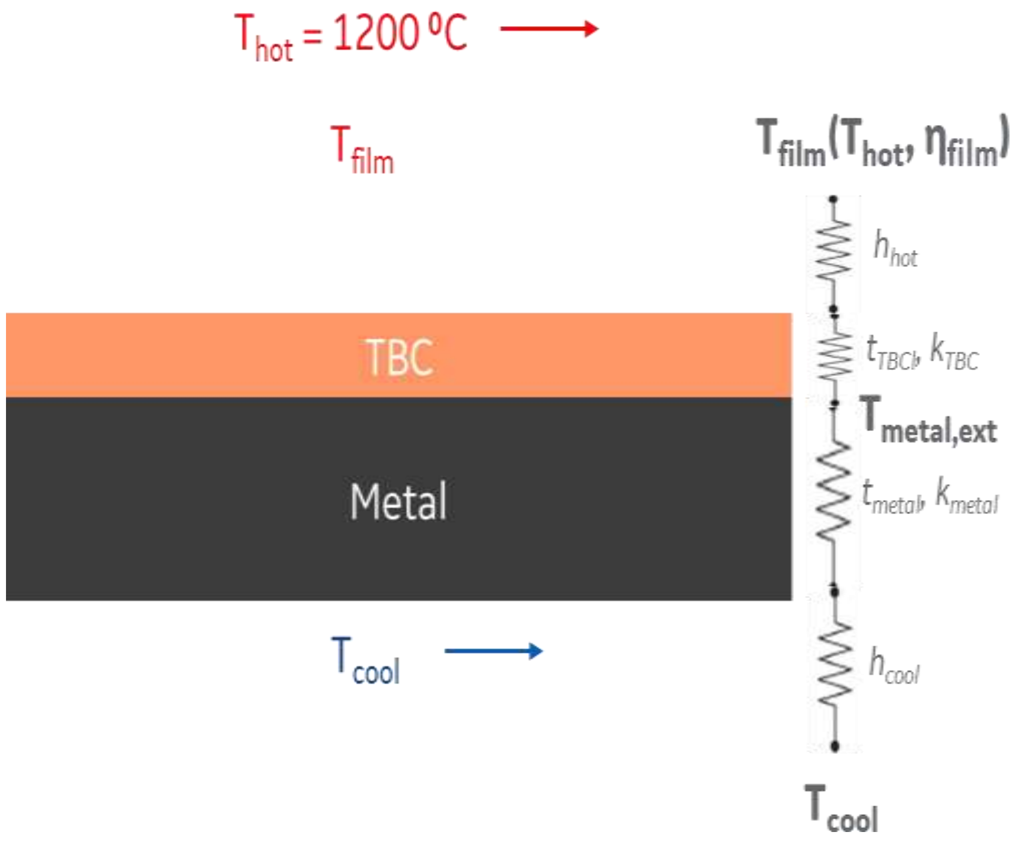
## Unbalance Response



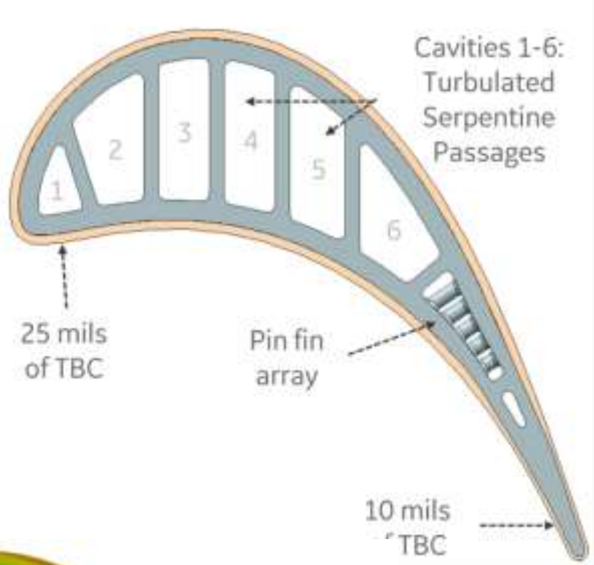
# 1D Heat Transfer Analysis

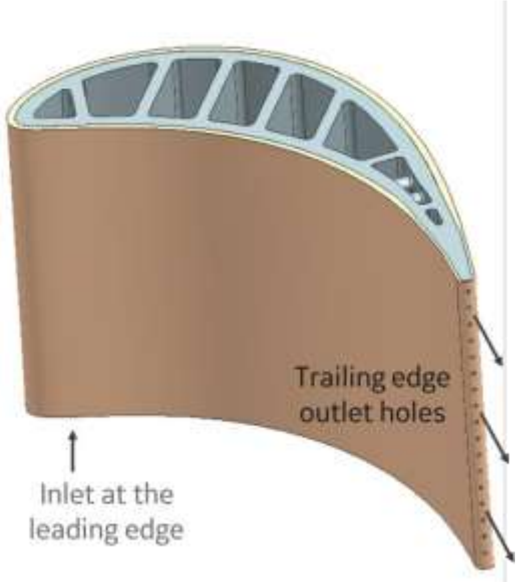
- High density of $CO_2$ results in high heat transfer coefficients
- Metal temperature target < 750°C
- Cooling temperature 430°C

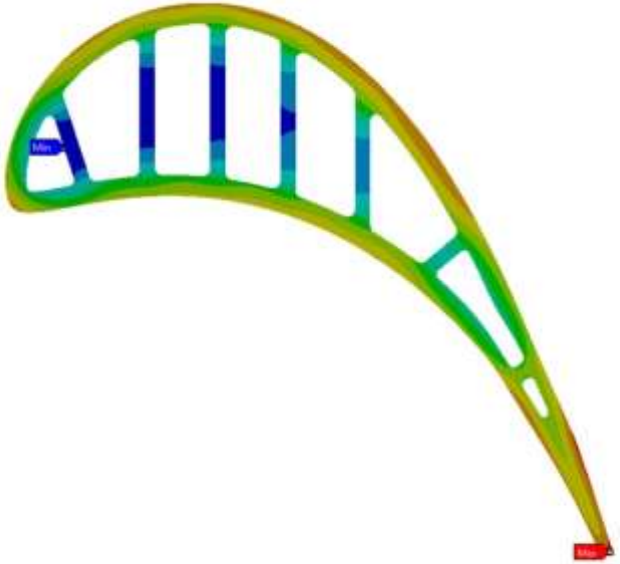
| Flow path | Stages | Cooling (% of Recycle-In) |
|---|---|---|
| Single | 4 | 4.2 |
| Single | 5 | 5.6 |
| Single | 6 | 7.5 |
| Single | 8 | 11.2 |
| Single | 10 | 15.9 |
| Double | 8 | 8.0 |
| Double | 10 | 9.2 |
| Double | 12 | 12.4 |

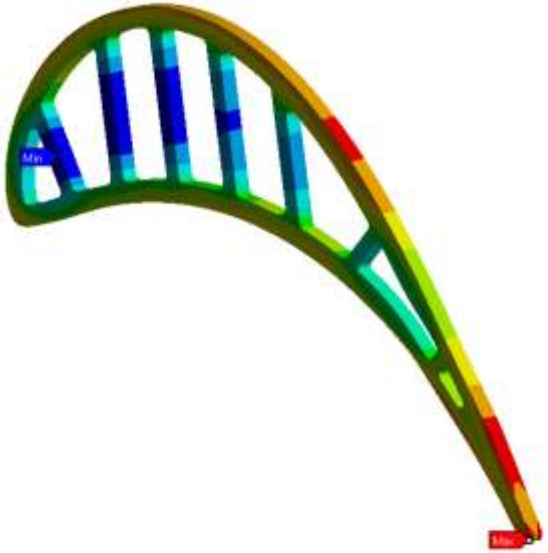


# 2D Heat Transfer Analysis

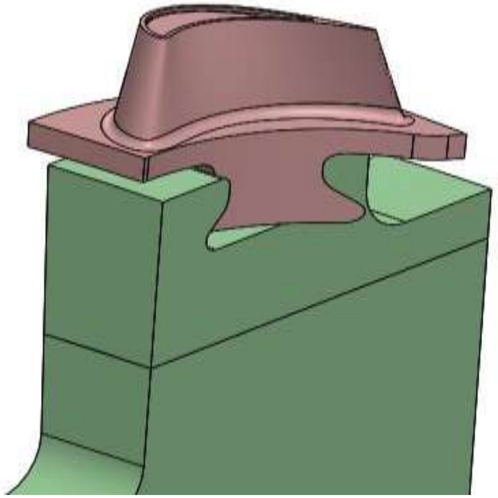


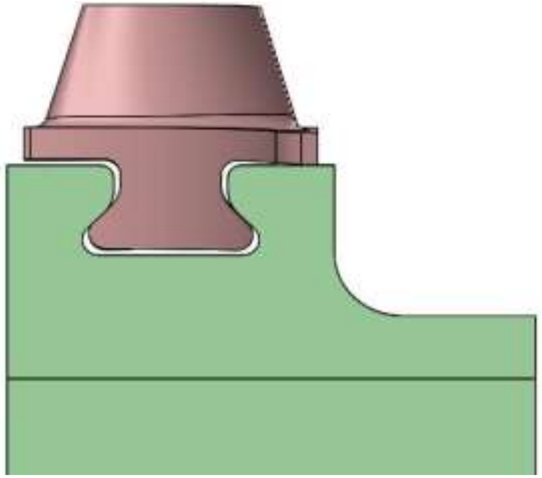



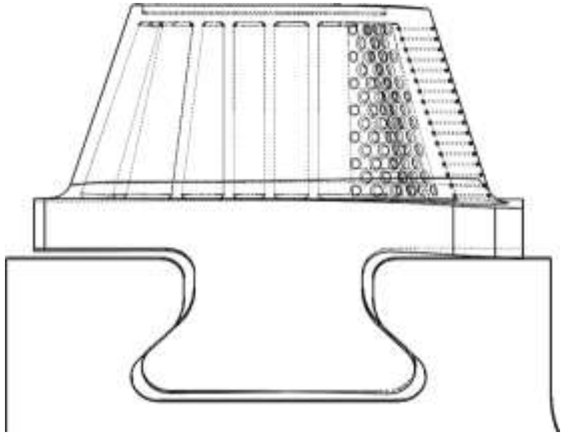



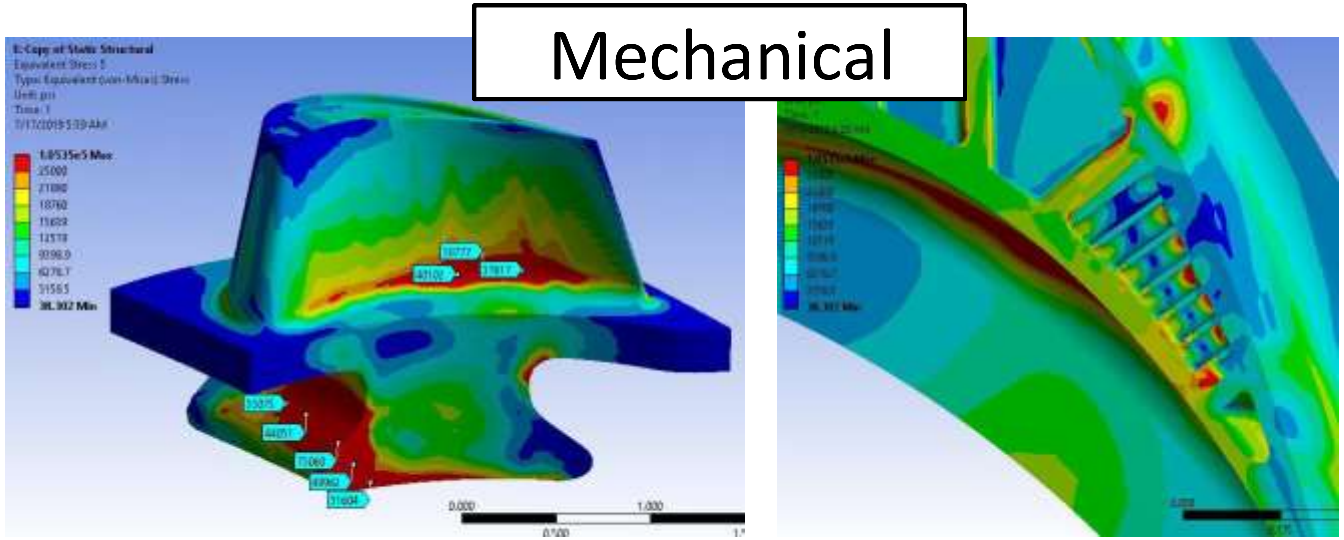


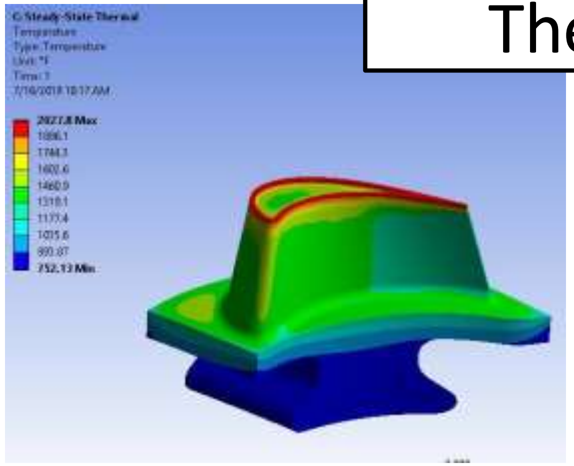
# 3D Blade Model

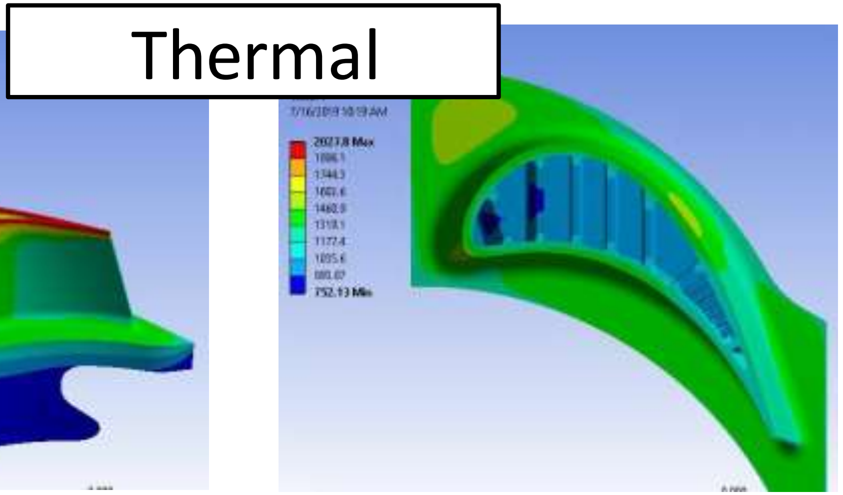




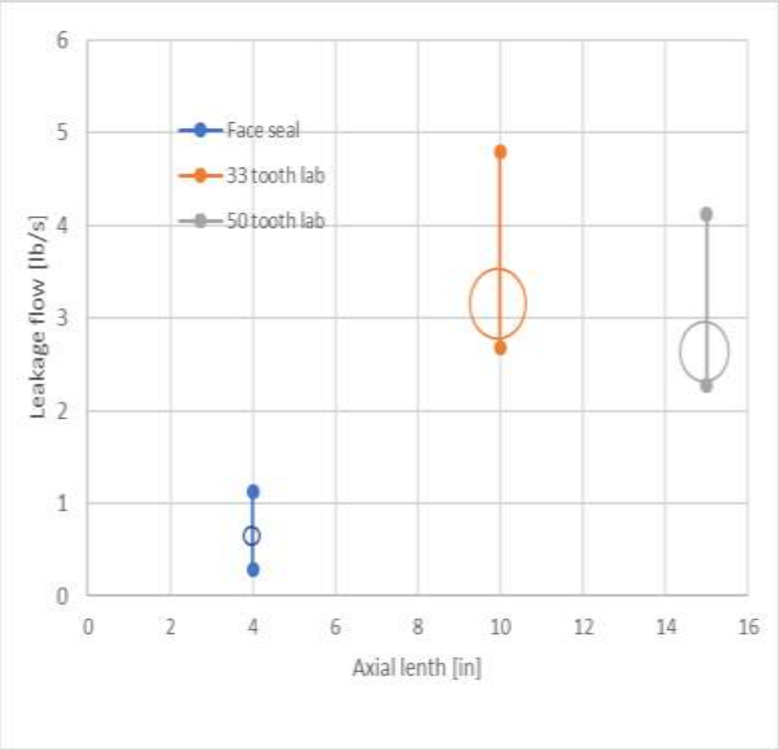


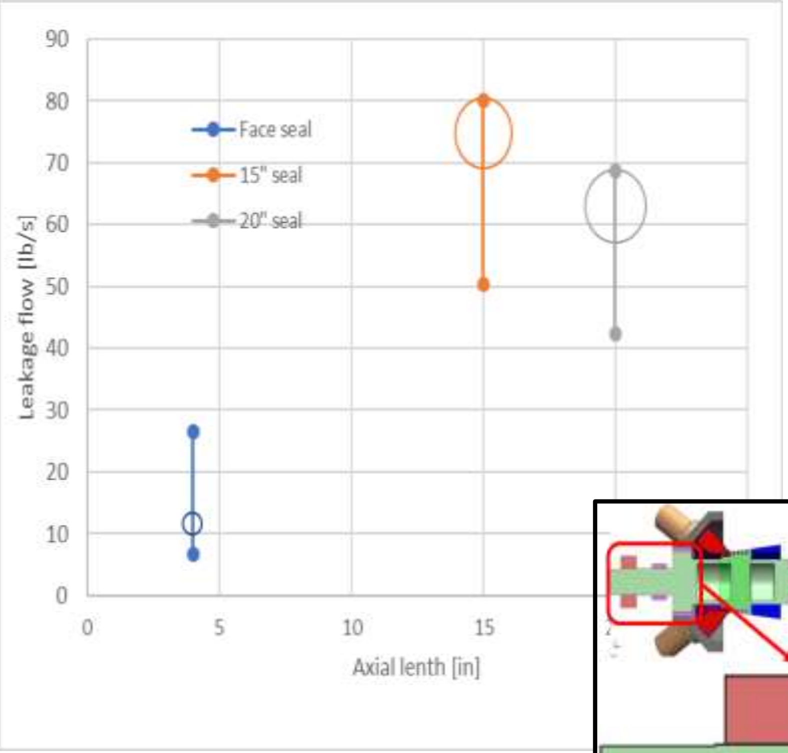


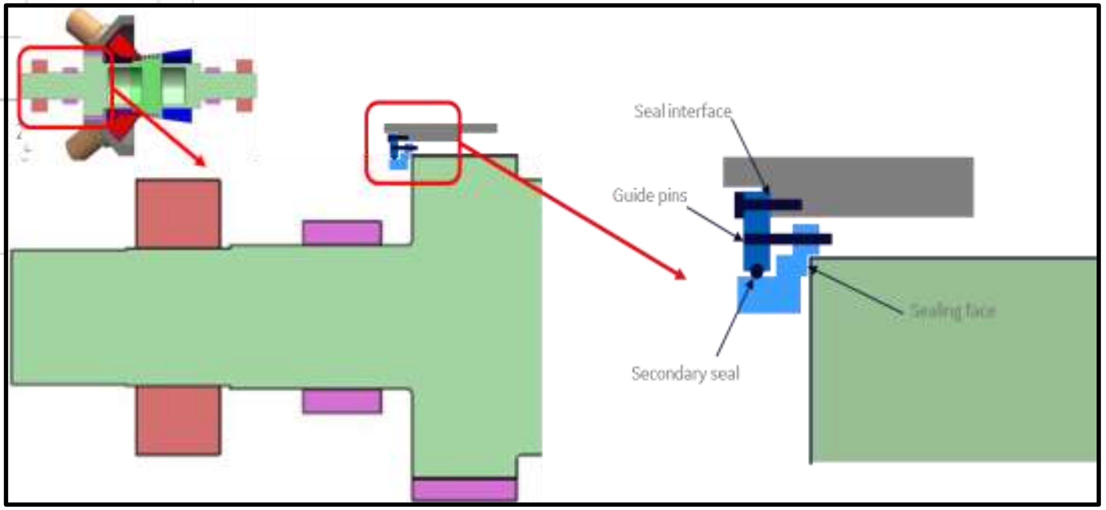





# Shaft End & Balance Piston Seal



# Turbine Conceptual Layout

Key information needed to start the case layout:

- Inlet and Exhaust Flow Conditions
  - -Temperature – Necessary materials and boundaries
  - -Pressure – Wall thicknesses and case configuration
  - -Volume Flow – Required flow area to keep velocities relatively low (<30 m/s)
- Aerodynamic Flowpath
  - -Hub Diameter – Maximum diameter of the main shaft
  - -Number of Stages – Required axial length for the turbine blades
  - -Configuration – Overhung, straddle, straight through, back-to-back
- Combustor Can Geometry
  - -Number of Cans – Radial spacing and organization around the case
  - -Can Diameter – Required penetrations and connections to the case

**Operating Conditions**

Below are some of the key operating conditions that affect the overall design of the turbine:

| | Inlet | Exhaust | Recycle | Cooling |
|---|---|---|---|---|
| Temperature [C] | 1,200.0 | 778.4 | 739.0 | 430 |
| Pressure [bar] | 305.0 | 30.0 | 315.0 | 316.5 |
| Flow [$m^3$/hr] | 30,544 | 223,808 | 13,745 | 1,043.8 |

# Turbine Conceptual Layout

**Rotor layout options**

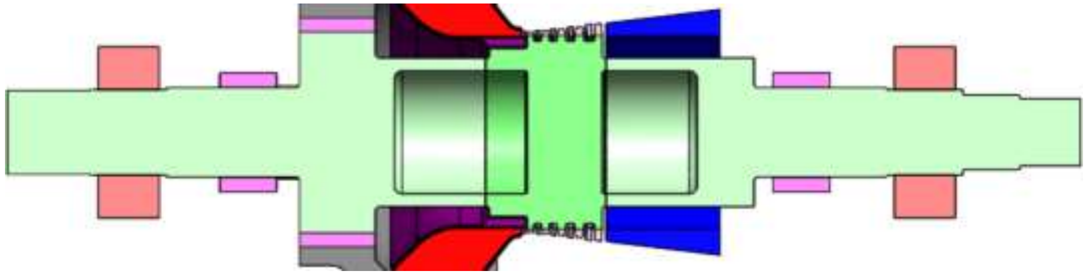
<u>5-Stage Straight Through</u>

- Fewer blades, shorter span, larger hub diameter
- While this is not advantageous for a case design, a larger hub diameter does lead to better rotordynamic stability
- Balance piston required but can be a source of damping

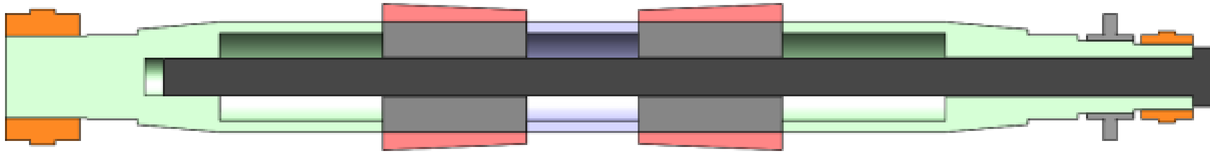
<u>12-Stage Back-to-Back</u>

- Smaller hub diameter which leads to thinner casings and lower stresses on the turbine blades
- Due to the back-to-back design, the pressure is balanced and there is no need for a balance piston to balance the thrust
- Rotor cooling seals required on both ends create more leakage than straight through design

5-Stage Straight Through Rotor Layout



12-Stage Back-to-Back Rotor Layout



# Turbine Conceptual Layout

1 – Main Cooling Supply to Turbine Case and Rotor

2 – Main Cooling Supply to Stators and Blade Shrouds

3 – Remaining Cooling Flow that Cools Recycle Flow Liner

4 – Balance Piston Flow

4a – Case cooling Flow

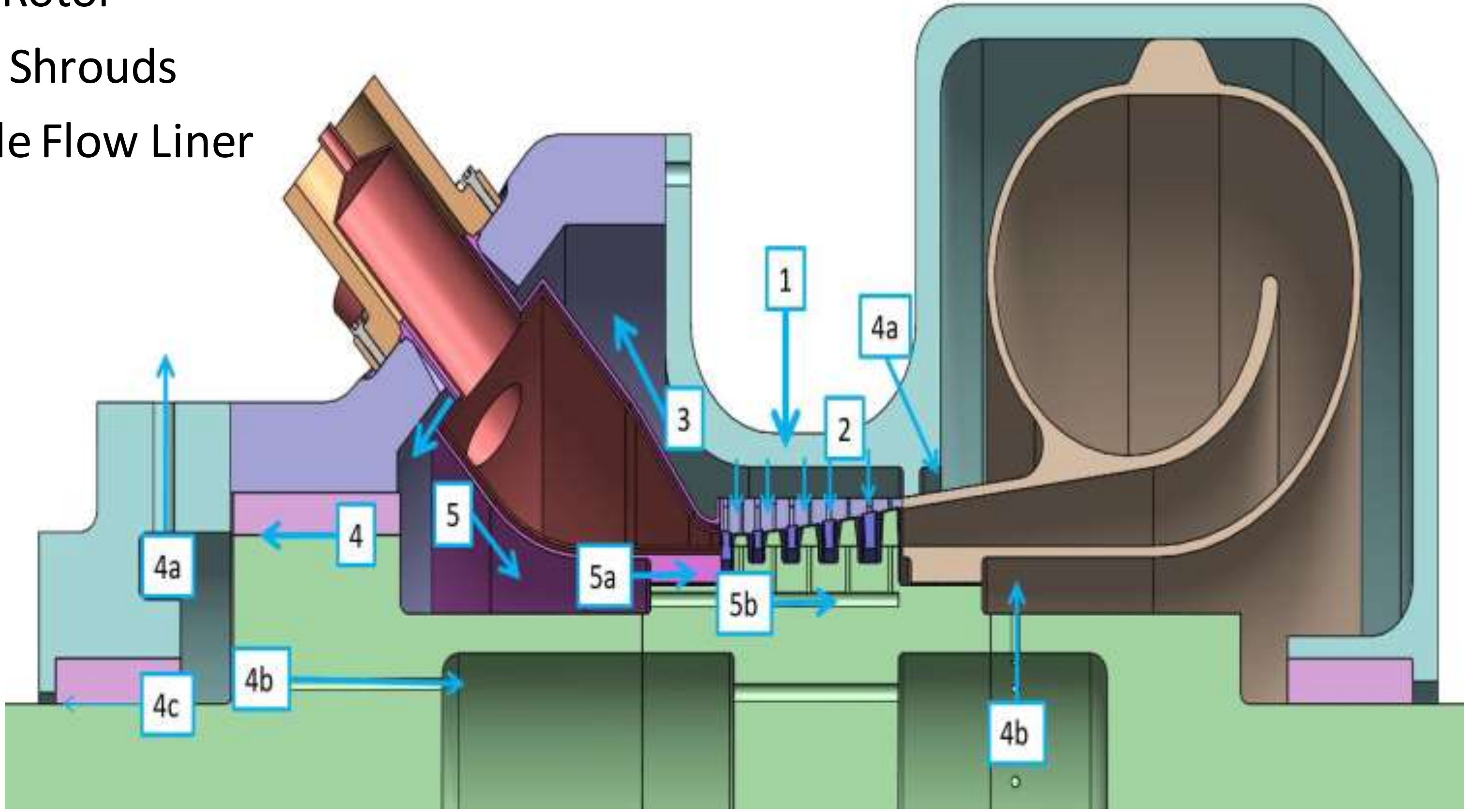
4b – Rotor and Case Cooling Flow

4c – End Seal Leakage

5 – Cooling Flow to Buffer Recycle Flow Liner

5a – Stage 1 Buffer Flow

5b – Blade Cooling Flow



# Summary of Project Goals & Outcomes

- Achieved greater than 58% thermal efficiency in the cycle analysis
- Developed aerodynamic design for first stage nozzle and turbine blade with efficiency greater than 85%
- Developed cooled nozzle and turbine blade design with metal temperature in high-stress areas less than 700°C.
- Developed a conceptual design for the oxy-fuel combustor to achieve a firing temperature of 1,200°C
- A conceptual layout completed including cooling scheme, seal layout, and rotordynamic evaluation
- Further development testing needed in kW and MW scale combustion testing
- Further development testing needed in blade cooling heat transfer coefficients
- Further development testing needed in material and TBC testing at 1,200°C in $CO_2$
- Phase 2 will complete detailed turbine design

# Development of Syngas Oxy-Combustion Turbine for Use in Advanced $sCO_2$ Power Cycles

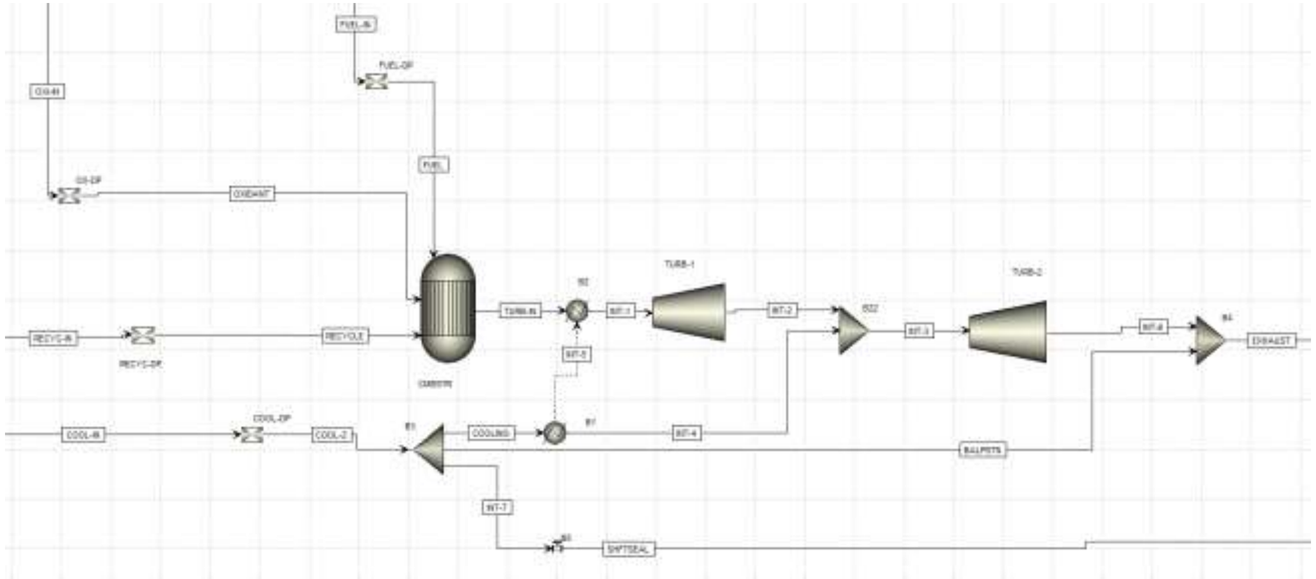
February 2, 2022

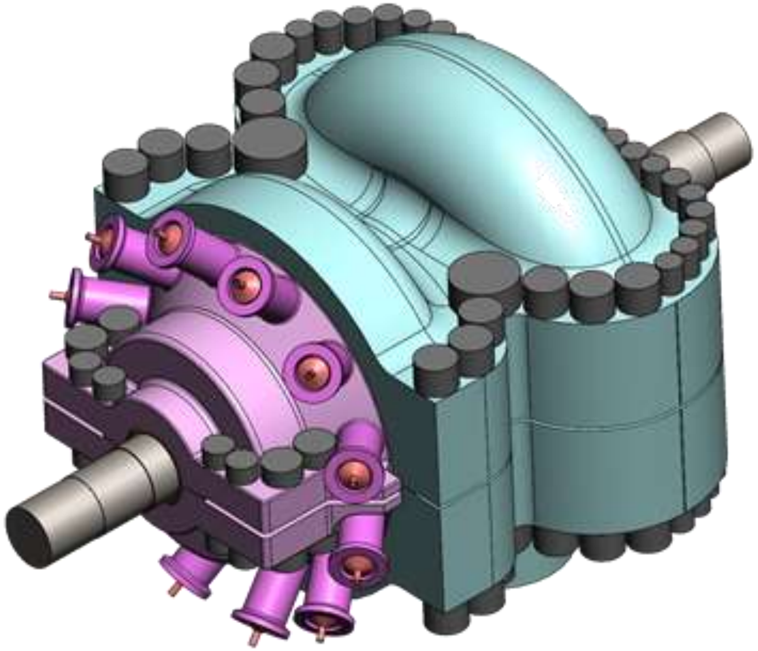
Department of Energy Award DE-FE0031929

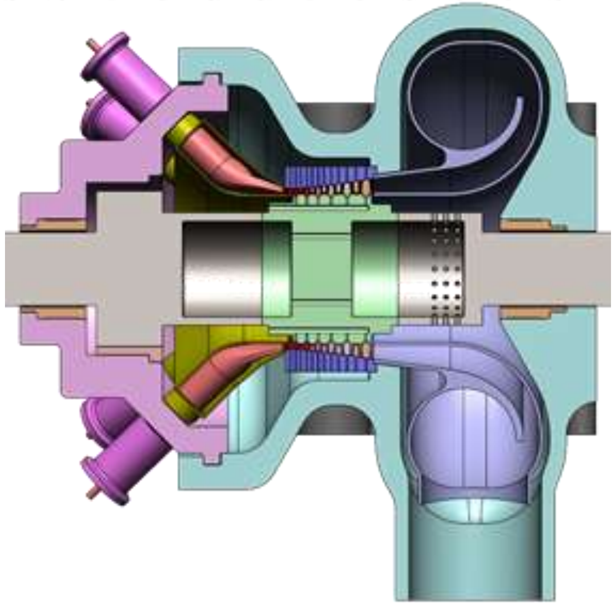
SOUTHWEST RESEARCH INSTITUTE

# Program Overview

- Build upon existing conceptual design and sizing work from DE-FE0031620 – “Development of Oxy-fuel Combustion Turbines with CO2 Dilution for Supercritical Carbon Dioxide (sCO2) Based Power Cycles”
  - Update Design and Cycle from that award for a Syngas Fired cycle rather than Natural Gas (able to be co-fired)
- Southwest Research Institute (Prime) – Stefan Cich, Jeff Moore, Florent Bocher
  - Turbine Design, Turbomachinery Testing with $sCO_2$, existing test loops and support equipment, material evaluation
- 8Rivers Capital, LLC – Jeremy Fetvedt
  - Facility with Commercial Potential for a 21st Century Power Plant
- Air Liquide – Bhupesh Dhungel
  - Combustion analysis and development. Performance Assessment
- General Electric GRC – Thomas Vandeputte
  - Turbomachinery design and seal development
- Electric Power Research Institute – George Booras
  - Techno Economic Assessment of the 21st Century Power Plant and industry insight into market potential
- Purdue University – Guillermo Paniagua
  - Aero design and testing with existing aerothermal test rigs
- University of Central Florida – Jayanta Kapat
  - Heat transfer expertise with $sCO_2$ and existing test rigs

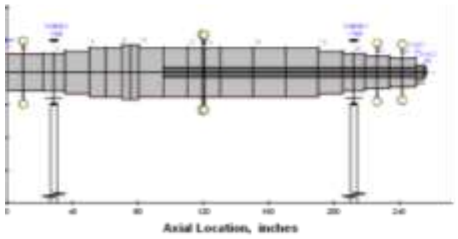


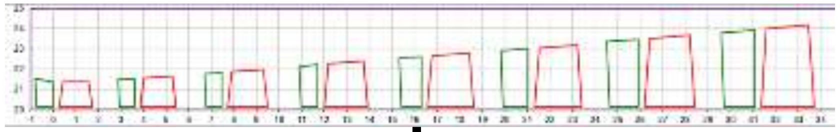


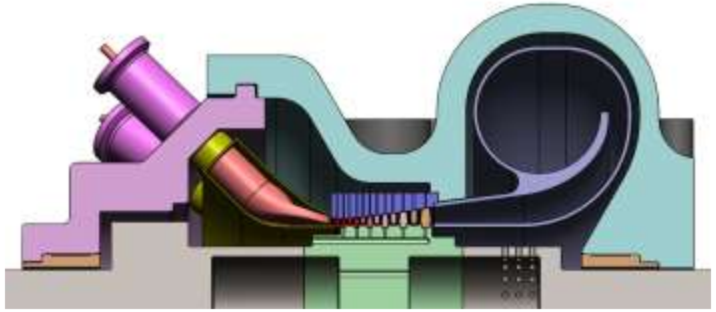


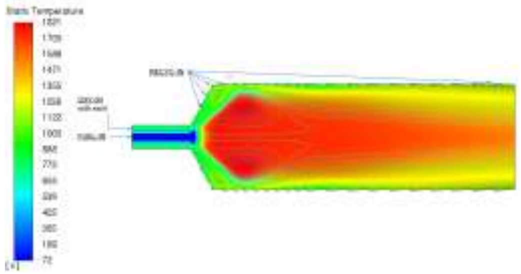
# Program Overview

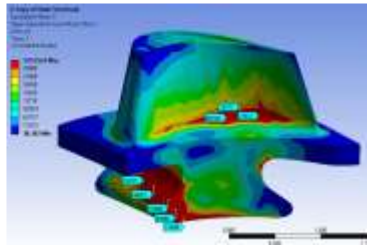
- Three Step Design Approach
  - Budget Period 1 – Conceptual Design
    - Turbine case and rotor, aerodynamic flowpath, and combustor layout with initial analysis and calculations to justify that the design can meet cycle requirements
  - Budget Period 2 – Preliminary Design
    - Updated design of all critical components (1$^{st}$ stage blade and vane, combustor, turbine case and rotor). All will undergo more detailed analysis and confirmation based on updated test data for key risk areas
  - Budget Period 3 – Detailed Design
    - Final analysis and manufacturing drawings to confirm design will meet final cycle model requirements and also allow for cost estimates of critical components
- All designs will be evaluated based on existing design codes and standards: API 612, API 684, ASME VIII-2, ASME B31-1 & 3



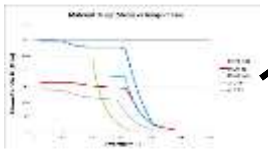







# Program Overview



Initial Cycle Model

Material Selection

Turbine Conceptual Layout

Seal Selection and Layout

Material Testing

Stress Analysis

Cooling Design

Steady State

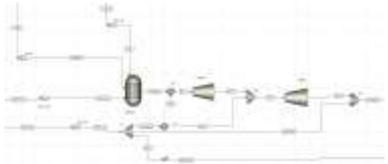
Thermal Transient

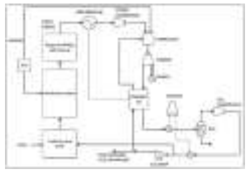
Containment

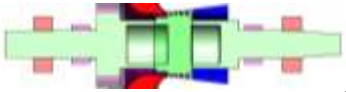
Preliminary Design

Thermal Analysis

Detailed Case Design







Initial Cycle Model

1D Mean Line Aero Design

HTC Testing Validation

Thermal Management Design

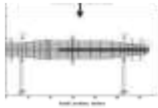
Rotor Conceptual Layout

Thermal Analysis – Steady and Transient

Stress Analysis

Rotordynamics

Detailed 1st Stage Blade and Vane

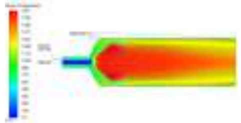


Detailed Rotor Design

Turbine Detailed Design

Final Cycle Model

Techno-Economic Assessment



Initial Cycle Model

Combustor Conceptual Layout

CFD

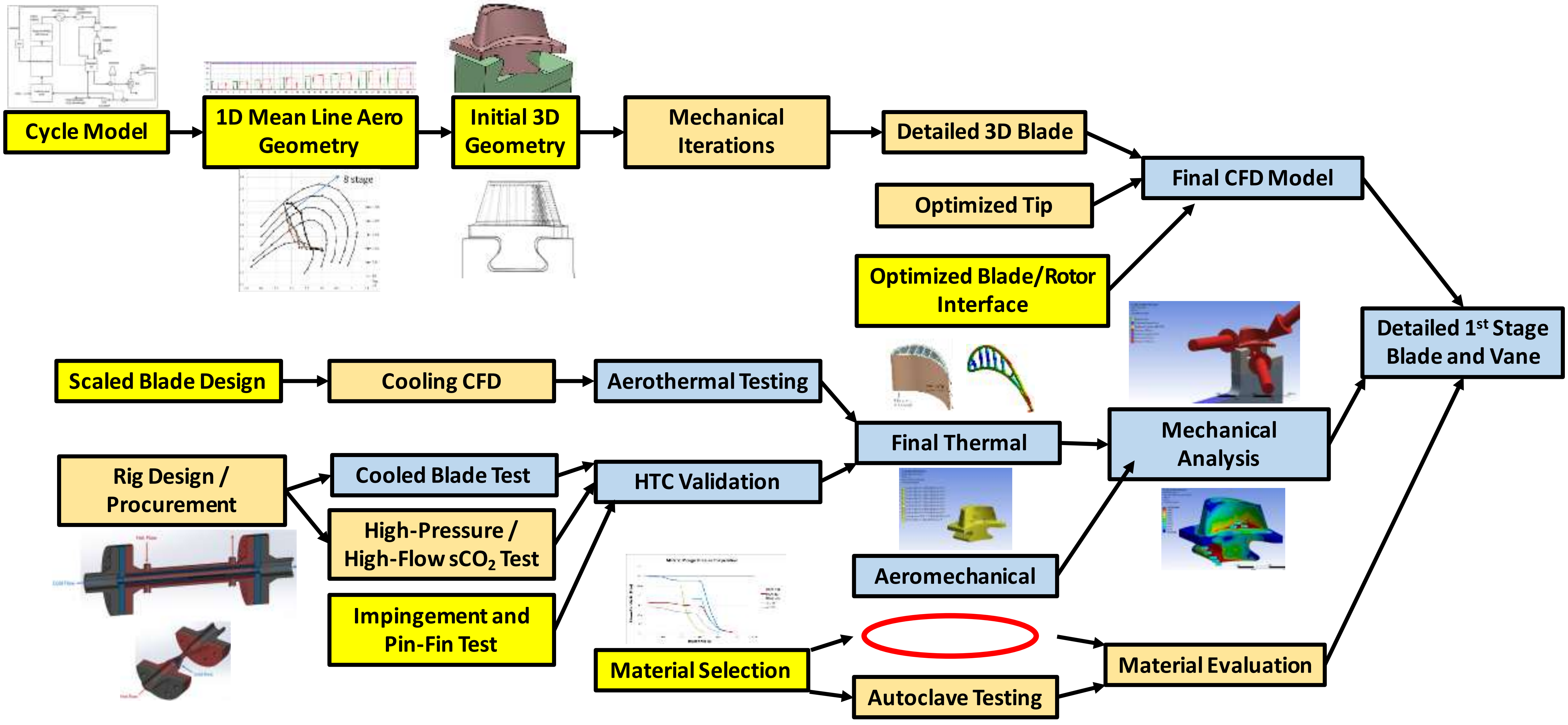
Material Selection

Containment

Combustor Preliminary Design

| |
|---|
| Budget Period 1 |
| Budget Period 2 |
| Budget Period 3 |
| Deliverable |

# Program Overview



# Program Overview – Key Risk Items

1. Turbine Layout (Task 1.2, 1.4, and 1.5)
   - Large scale, industrial high-pressure turbine (315 bar) with high-pressure oxy-fuel combustor in a closed-loop system
     - Closed-loop system → addition of pipe loads due to thermal growth acting on all critical components
     - While the system does produce its own $CO_2$, need to prevent $CO_2$ leakage to the atmosphere
     - Due to size, there is a desire for a horizontal split casing for ease of maintenance → high pressure metal-to-metal face seal at split joint
     - Easier maintenance → option for cheaper internal high temperature materials that can be replaced periodically to improve performance and reduce overall cost
   - Industrial gas turbines – Higher temperature at lower pressures in an open-loop system
   - Steam turbines – Lower temperatures and pressures
2. Sealing Technology (Task 1.4)
   - End seals, internal seals, blade to stator seals, split case sealing, balance piston, axial face seal
   - For leakage to atmosphere: end seals and high temperature case sealing
     - End seals will see around 30 bar. Longer labyrinth seals can be implemented for comparable leakage to face seal. Labyrinth seals can also be designed with a lower pressure reservoir for re-injection at 30 bar
     - Case will see 315 bar
3. High Temperature Blade Materials (Task 1.6)
   - Smaller blades lead to manufacturing challenges. Potential for Additive Manufacturing (AM) of turbine blades
   - Evaluate properties of AM materials vs Castings
   - Evaluate impact of Syngas byproducts on materials in the high-pressure and high-temperature environment
4. Thermal Barrier Coatings (Task 1.6)
   - Similar to blade materials, necessary to look at impact on material performance from byproducts in syngas
   - Due to operating nature of this technology, look at thermal cyclic performance of TBCs
5. Heat Transfer Coefficients for high relative mach # process flow and high Reynold's number cooling flow (Task 1.3)
   - Predicted cooling flow will be at Reynolds # > 250,000
   - Need to evaluate impact on heat transfer performance with $sCO_2$ to determine design limits and what kind of enhancements will be required to effectively cool blades and vanes
   - More efficient cooling → less cooling flow and higher efficiency or easier to manufacture materials

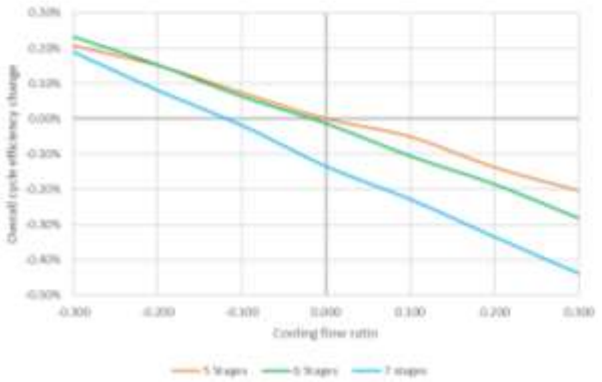
# BP1 – Technical Summary

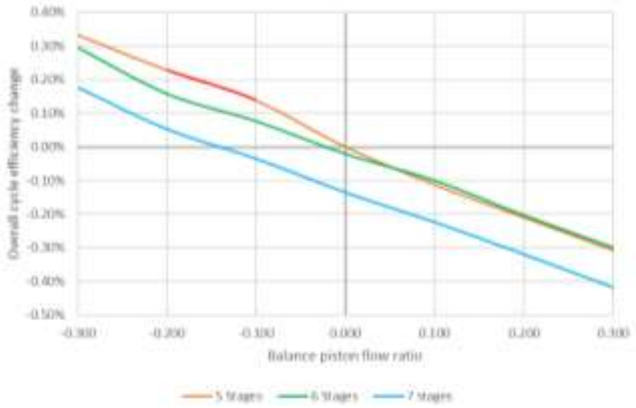
- Task 1.2 – Initial Syngas Combustion Cycle
  - Modify a 100% Natural gas Oxy-Combustion Cycle with syngas. Requires addition of Gasifier and Cleanup
  - Look at impact of various syngas (high-CO & high-$H_2$) fuels and evaluate performance
- Task 1.3 – Heat Transfer Validation
  - Fundamental heat transfer test rig (impingement and pin-fin) design, manufacturing, and commissioning
  - High-flow, high-Re # representative heat transfer test rig (internal blade passages & representative blade) design and review
  - Assessment of internal cooling options and how they can be applied and validated
- Task 1.4 – Turbine Conceptual Design
  - 1D Meanline flowpath design that will meet aero, cycle, and mechanical requirements
  - Optimization of 1$^{st}$ Stage Vane & Blade flowpath
  - Conceptual design of turbine rotor, case, seals, and thermal management
- Task 1.5 – Combustor Conceptual Design
  - Detailed assessment of Combustor layout that will fit into the chosen case layout
  - Update analysis to account to different fuels, downstream stator vanes, and non-uniform spacing as required by the case
- Task 1.6 – Material Testing
  - Evaluation of potential materials that will be used in the final turbine design along with test plan to validate the materials
  - Procurement of high temperature equipment for autoclave and cyclic thermal testing

# Task 1.2 – Cycle Model

- Two main impacts on cycle model when compared to a Natural Gas Oxy-Combustion Cycle
  - Addition of Gasifier and Syngas Cleanup. These impact the overall cycle performance as they are a direct efficiency loss. Turbine parameters are held constant (Inlet temperature, pressure, and volume flow). This is possible due to majority of flow being recycled $CO_2$
  - Evaluation of Syngas fuels (high-CO & high-$H_2$) vs Natural Gas. Look at impact on mass flow, temperatures, and efficiency
- While the turbine performance is not impacted by changing fuels, the combustor performance is significantly impacted
  - Fuel flow rate increases by 4-5X
  - Oxygen flowrate decreases by 50%
  - In order to maintain proper combustor performance, Fuel and Oxygen flowrates need to be consistent
  - Look at options for multiple nozzles and pre-mixing with recycled $CO_2$
- Turbine Design Conditions:
  - Flow rate: 30,000 $m^3$/hr
  - Pressure: 315 bar
  - Temperature: 706C (Recycle Flow sections)
  - Fuel Nozzle: 1,042 $m^3$/hr (High-$H_2$ Syngas)
  - Oxygen Nozzle: 6,000 $m^3$/hr (100% $CH_4$)
  - Power: 450 $MW_{mech}$

| | | NG | 2.45 CO:H2 | 0.9 CO:H2 |
|---|---|---|---|---|
| FUEL-IN | kg/hr | 38,843 | 204,771 | 191,320 |
| | m3/hr | 224.9 | 962.8 | 1,041.4 |
| LHV | MJ/kg | 50.0 | 9.8 | 10.3 |
| | MWt | 539.8 | 558.2 | 547.6 |
| OXI-IN | C | 687.0 | 695.8 | 705.8 |
| | kg/hr | 890,365 | 682,145 | 691,070 |
| | m3/hr | 6,013 | 4,645 | 4,754 |
| RECYC-IN | C | 687.2 | 695.8 | 706.0 |
| | kg/hr | 2,055,954 | 2,166,745 | 2,125,727 |
| | m3/hr | 13,076 | 13,883 | 13,765 |
| TURB-IN | C | 1,149.9 | 1,150.1 | 1,150.4 |
| | bar | 305.0 | 305.0 | 305.0 |
| | kg/hr | 2,985,162 | 3,053,660 | 3,008,117 |
| | m3/hr | 29,559 | 29,551 | 29,553 |
| % diff into turbine | kg/hr | Baseline | 2.3% | 0.8% |

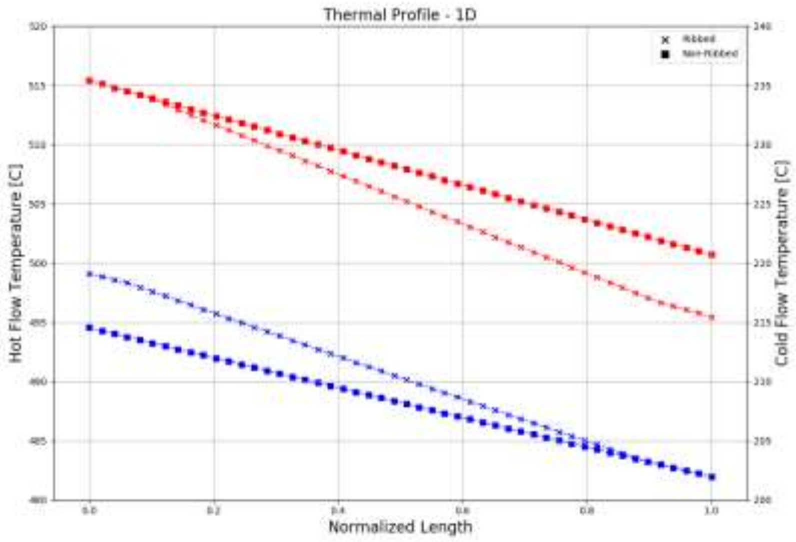


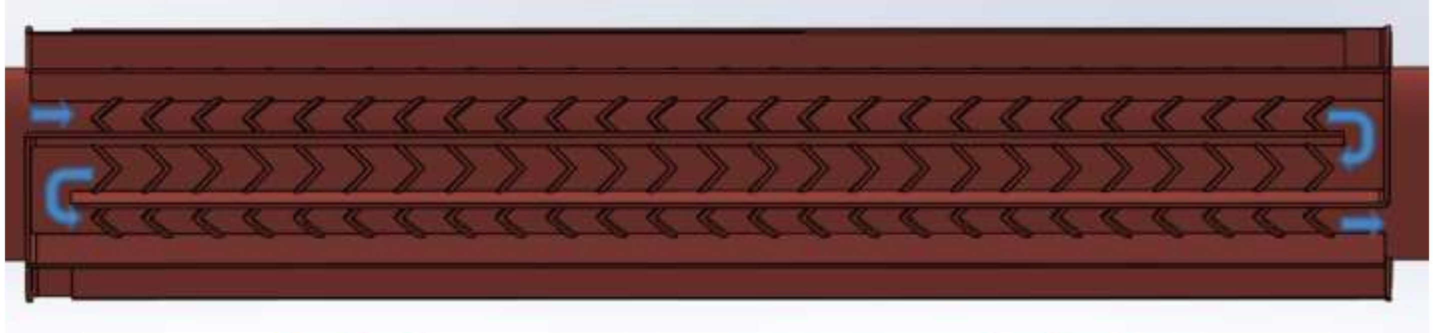


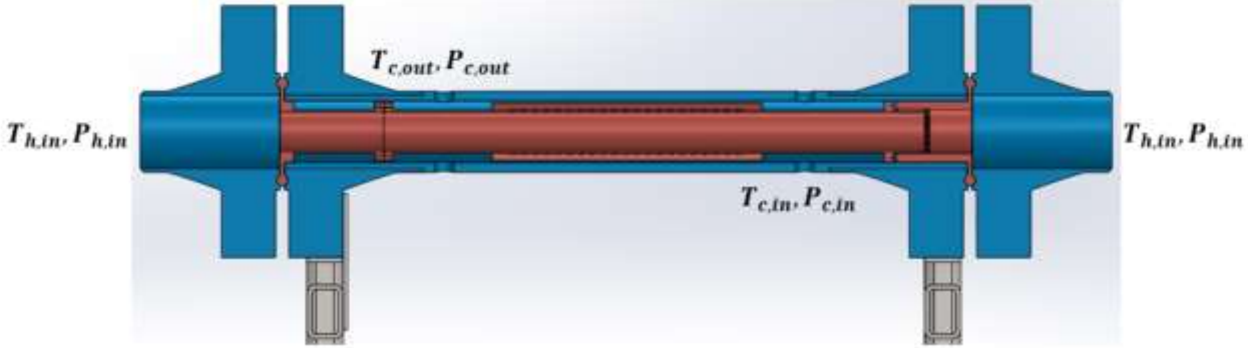
# Task 1.3 – Heat Transfer Validation

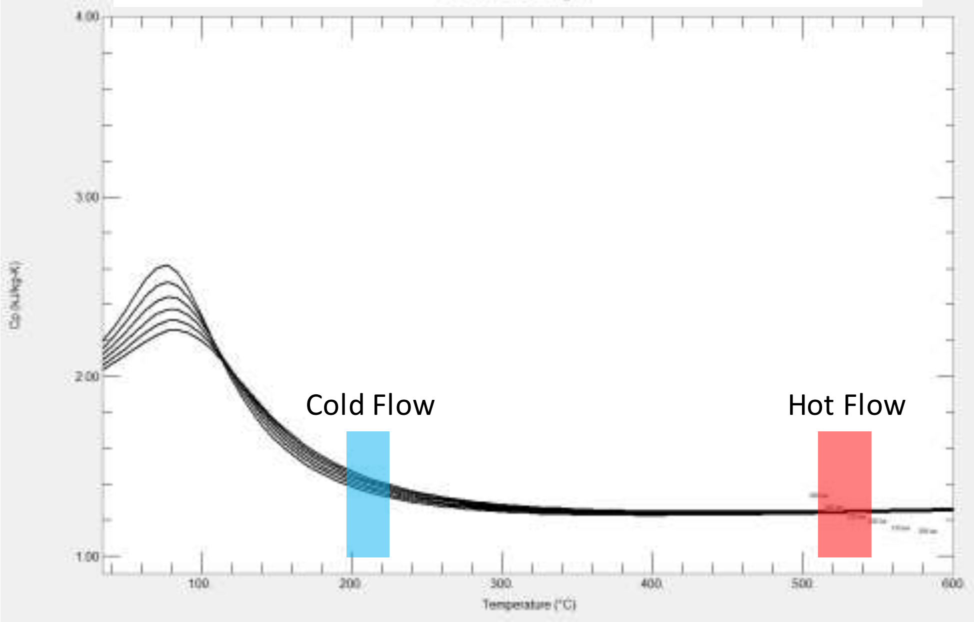
<u>Task 1.3.1 – High Reynolds Number $sCO_2$ Test Rig Design</u>

- Design a high flow $sCO_2$ heat transfer rig that can evaluate different types of internal HTC enhancements for blade cooling flow
- Critical to understand total error in measurements
- Lower dT and Length → Large Errors
- Single pass leads to 15-20°C Temperature Rise. Looking at multi-pass option
- Important to avoid near dome temperatures with high variations in fluid properties.
- Currently looking at operating around 200°C for the cold flow and around 525°C for the hot flow.



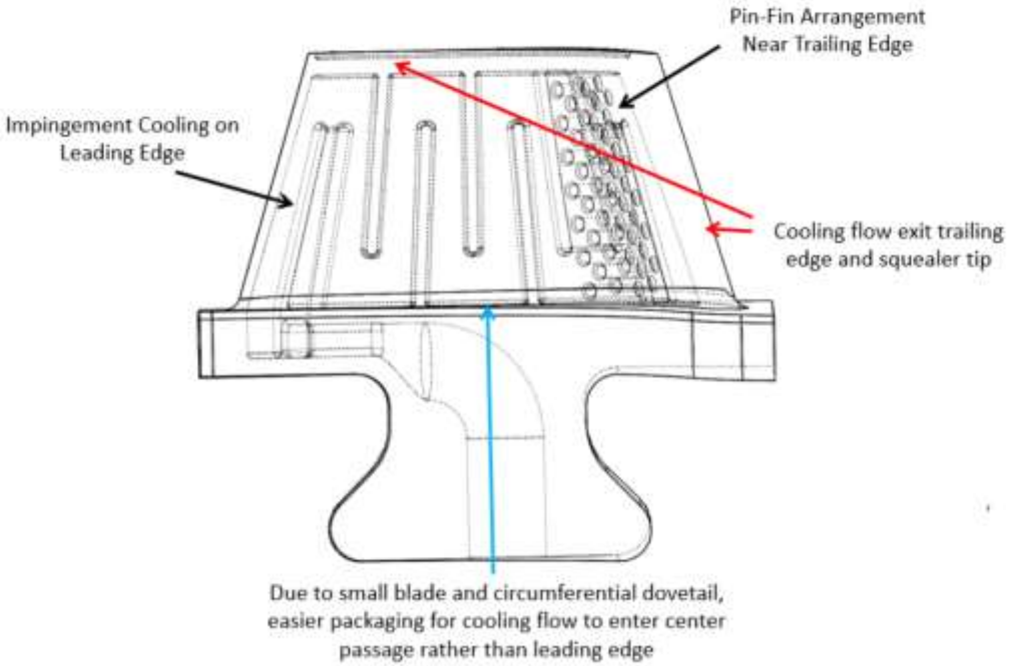


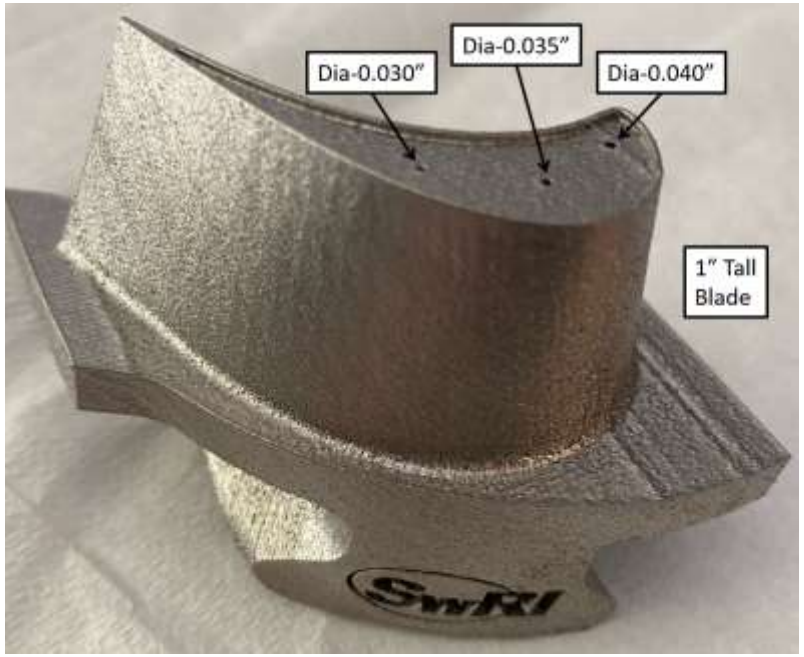



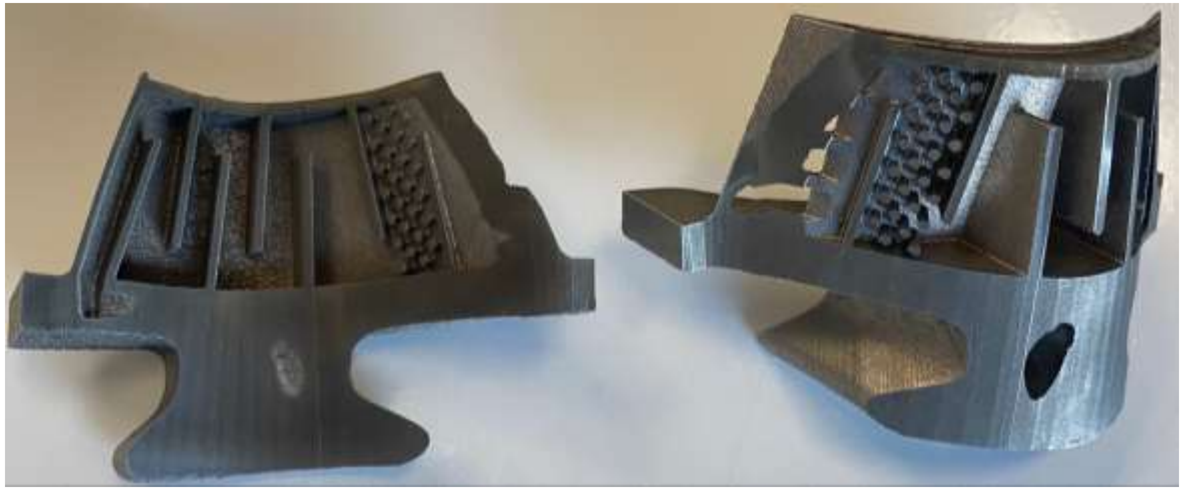
# Task 1.3 – Heat Transfer Validation

## Task 1.3.2 – Impingement and Pin-Fin Assessment

- Evaluate potential areas for various heat transfer enhancements (pins, fins, impingement, serpentine, surface roughness)
- Manufacturing options impact potential features. Currently looking at AM parts. Key questions on AM
  - Internal surface roughness?
  - Accuracy of internal features (pins, fins, serpentine)
  - Minimum diameter for impingement cooling holes (Trial Prints → 0.030" Diameter)
- Due to method of attachment, central fed serpentines with leading edge impingement cooling will be ideal



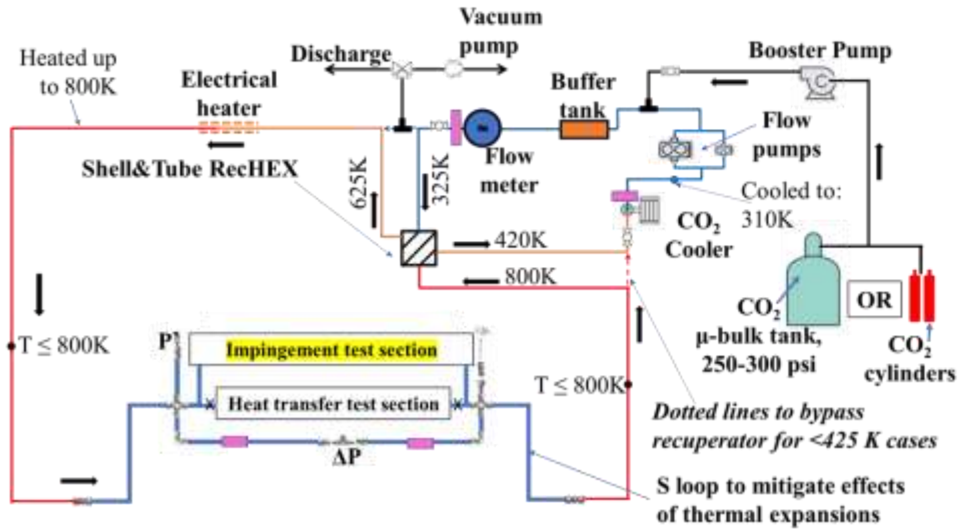



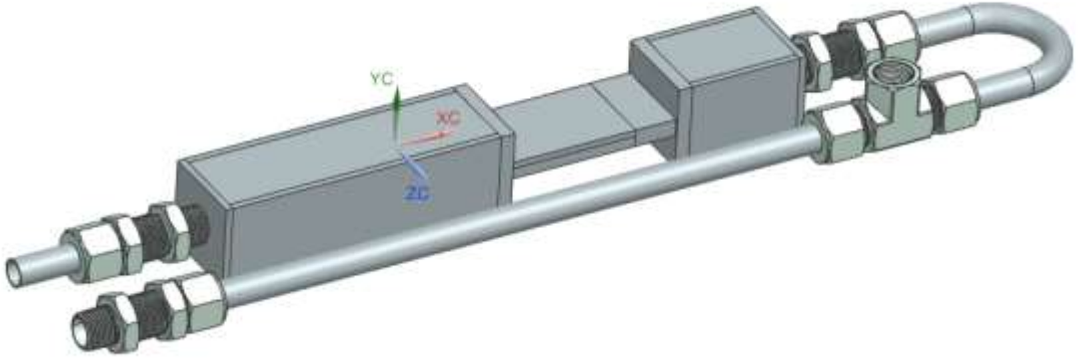
# Task 1.3 – Heat Transfer Validation

<u>Task 1.3.3 – Rig Adaption for $sCO_2$</u>

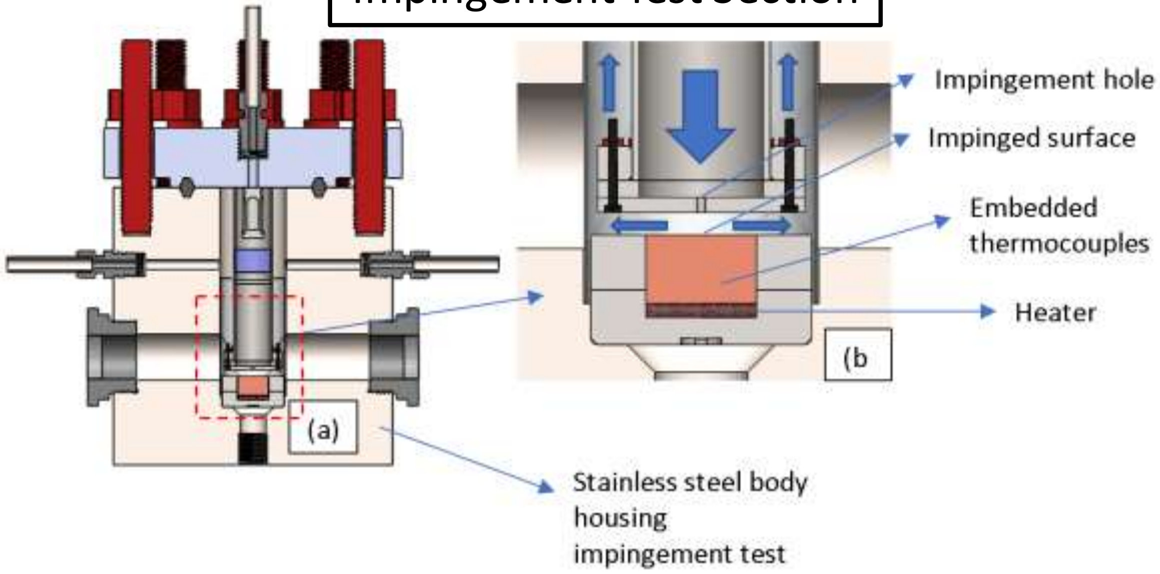
- Impingement Test Section
  - This test will involve a single jet with a heated copper plate
  - Heat transfer will be measured by measuring required energy input into the copper plate to maintain temperature
  - Current limitations allow for a single hole to be tested, but that geometry can be changed with the modular plate on the inside
- Pin-Fin Test Section
  - Test section will be inside a pressurized cylinder to reduce dP across test section
  - Modulus test section that will allow for the testing of various pin-fin arrays
- Preliminary goal is to compare to air tests and look at trends with $sCO_2$. This will allow for use of existing data to aid in design optimization
- Testing in BP3 will be focused on mimicking geometry inside the updated blade




Pin-Fin Test Section



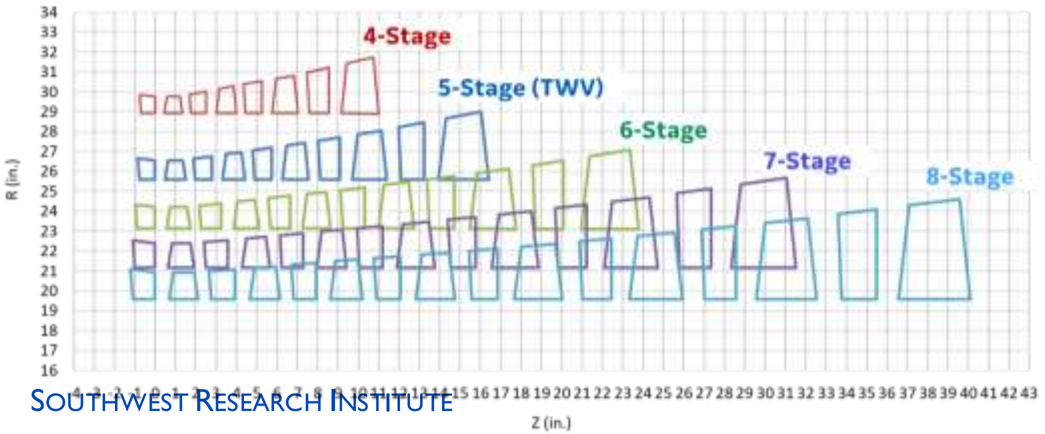

Impingement Test Section

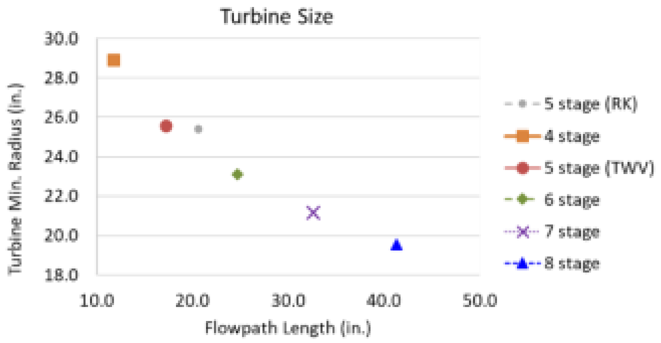


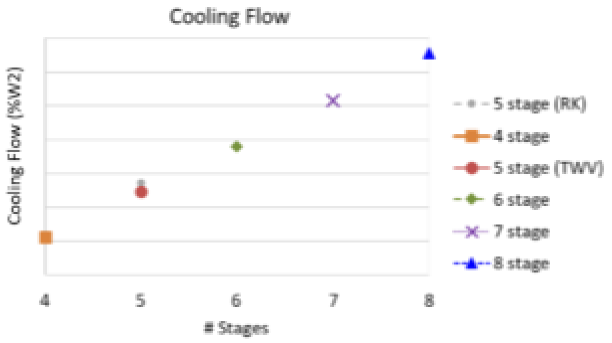
# Task 1.4 – Turbine Conceptual Design

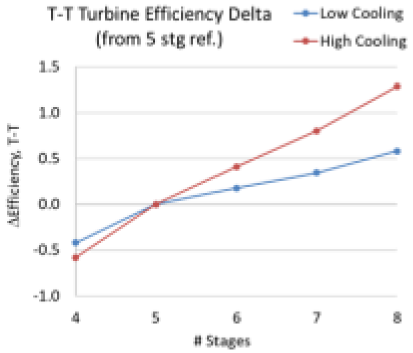
Task 1.4.1 – Turbine Meanline Layout

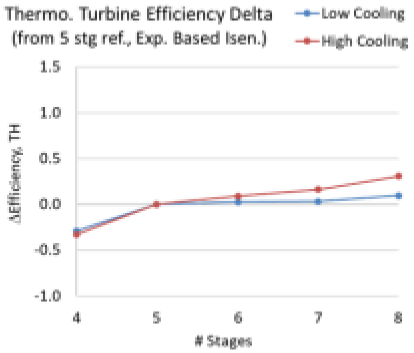
- With updated cycle modeling complete, early work was focused on updating the Turbine Meanline Layout and picking the optimal flowpath for this turbine
- Original design was a very high level layout and needed to be updated with more time and funding a long with more trade studies
  - Model Updates
    - Added cooling flow per stage
    - Performed thermo balance between each stage with added cooling flow
    - Included updated assumptions for secondary leakages
  - Model Trade Studies
    - Higher Stage Count
      - Benefits: Taller blades, smaller seal diameters (less leakage), higher aero efficiency, and lower velocities at the exhaust leading to less pressure recovery in the diffuser
      - Negatives: Smaller hub diameter (reduced rotor stiffness), longer axial span (reduced rotor stiffness), and increased cooling flow
- Rotordynamic concerns ruled out the 8 stage design
- Manufacturing and performance concerns ruled out 4 and 5 stage due to balde height
- **6-Stage design chosen**

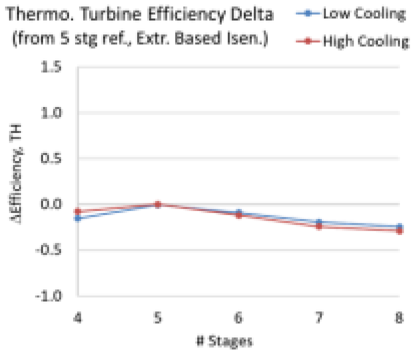


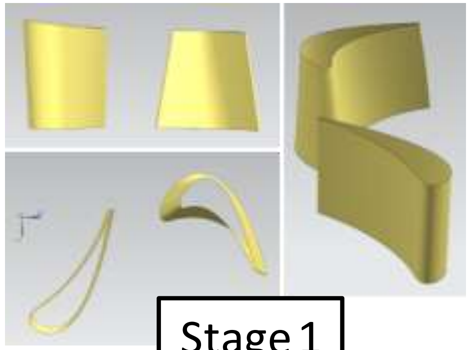



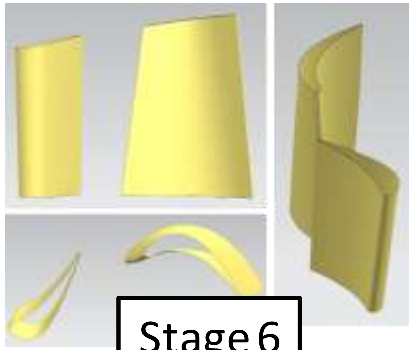
# Task 1.4 – Turbine Conceptual Design

## Task 1.4.2 – 3D Modeling and Analysis of 1st Stage

- 3D Models and Meanline produced by GE are passed to Purdue for Optimization
- Purdue is performing optimization sweeps by creating a parameterized linear model that matches the 3D smooth model closely
- Parameters of Concern:
  - Optimization focus: Sweep, stacking, lean, stagger, Camber, Span
  - Aeromechanical Focus: LE and TE Radius, Number of Blades, Max Lean and curvature
- Current plan is to run optimization studies and look at impact on mechanical performance and manufacturing to impose additional limits as necessary
- Optimization will look at improving aero efficiency and reducing heat flux to the blade

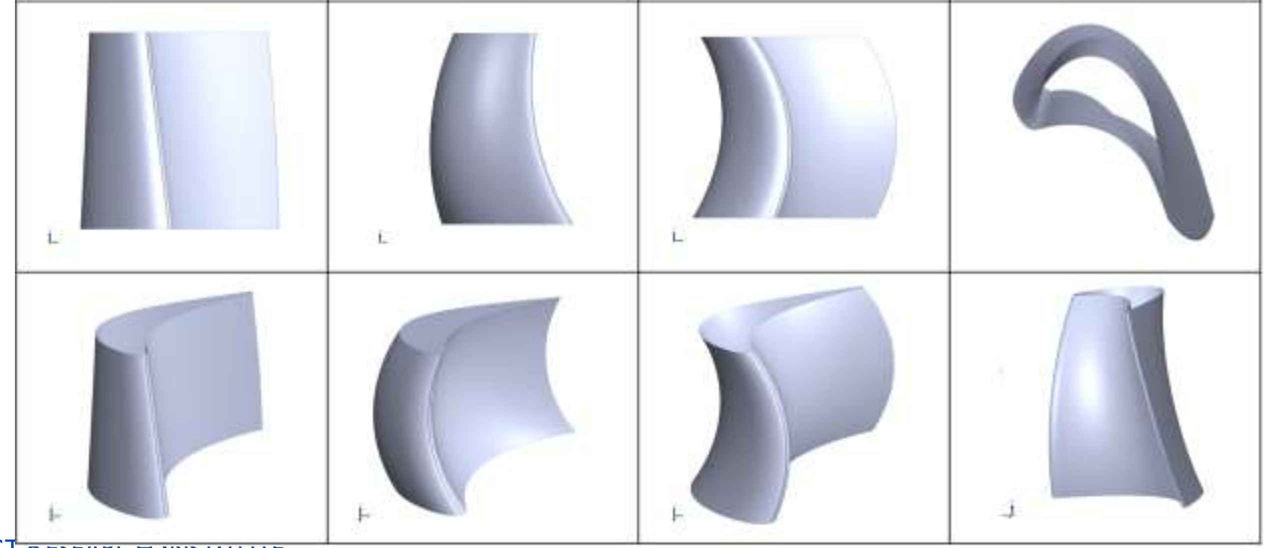


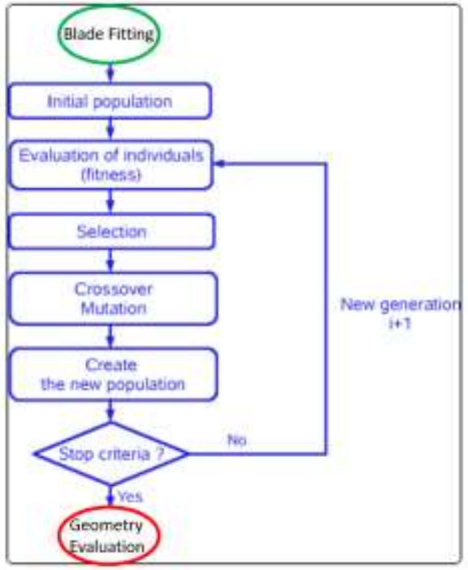
Stage 1

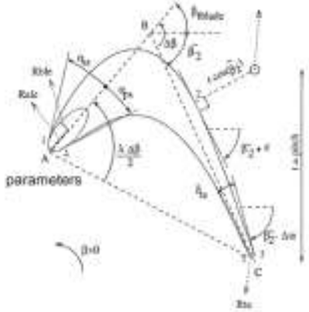


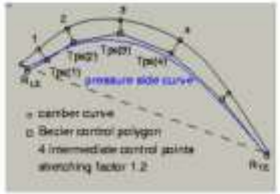
Stage 6

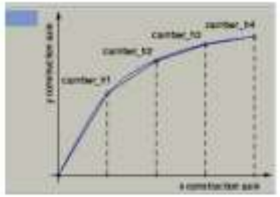
| Baseline | Maximum Lean (-15 deg) | Maximum Lean (+15 deg) | Maximum Stagger Differential |
|---|---|---|---|





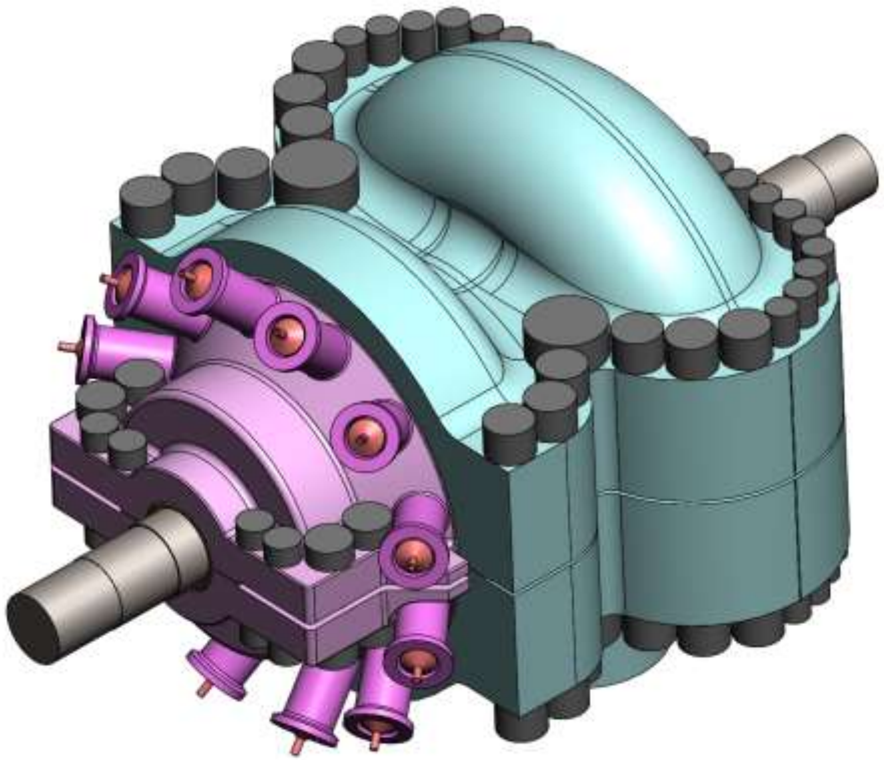



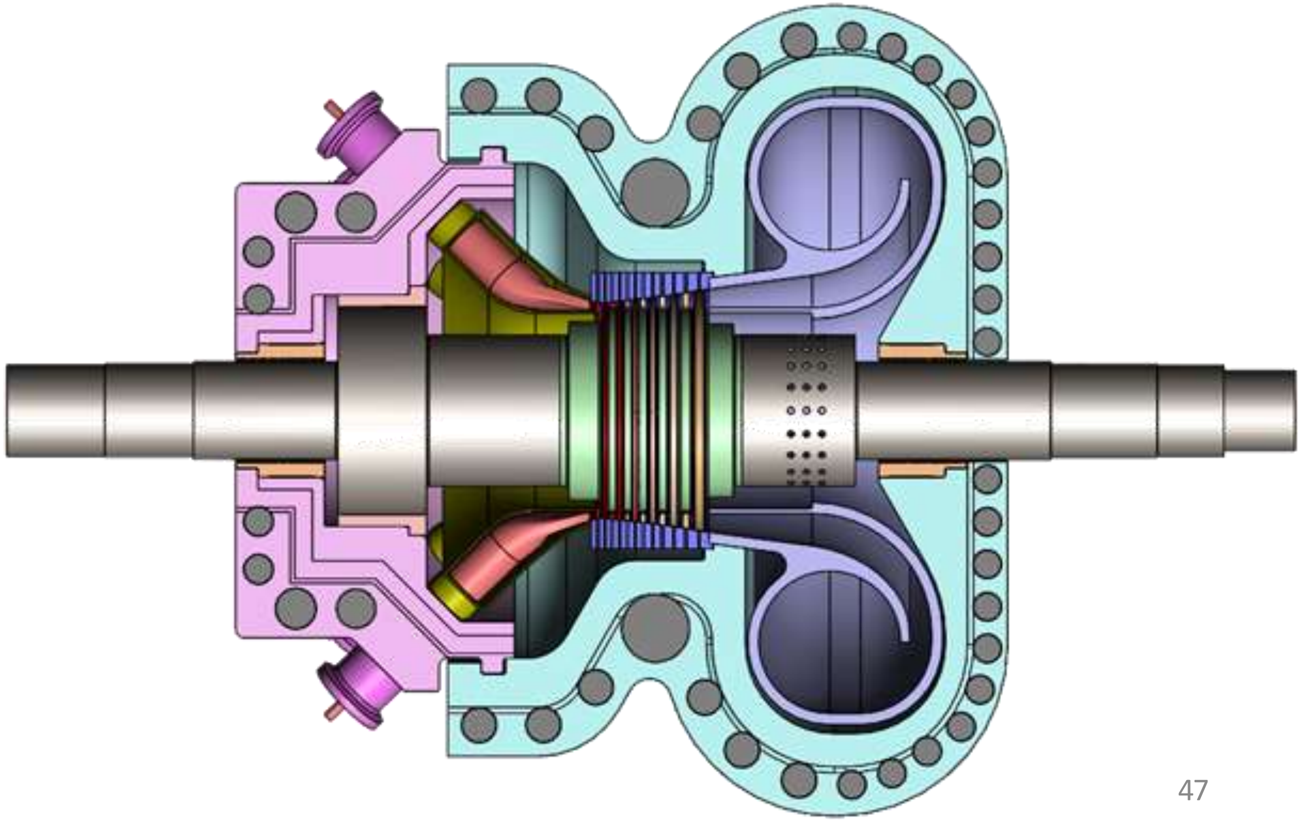



# Task 1.4 – Turbine Conceptual Design

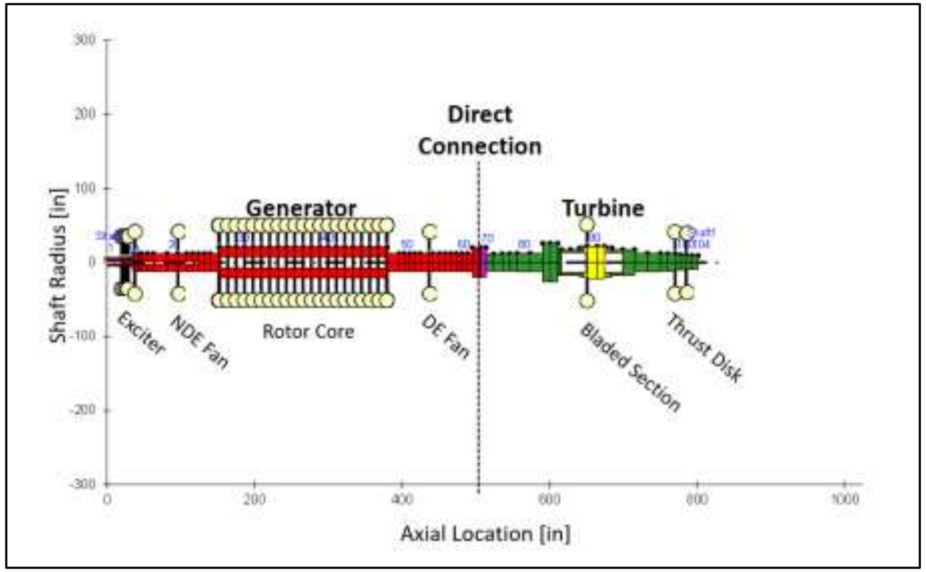
Task 1.4.5 – Conceptual Layout

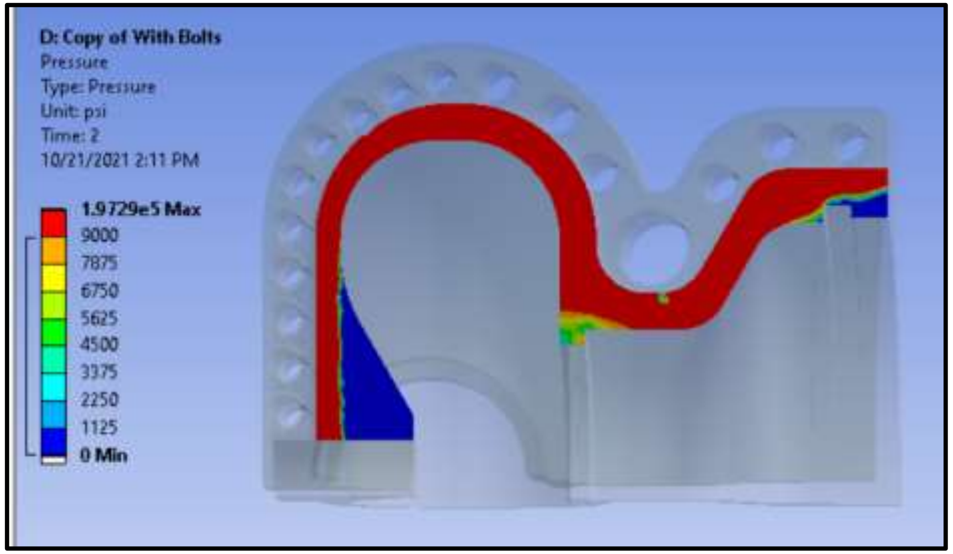
- Main focus of BP1 has been on updating the case layout with the chosen aerodynamic flowpath. The main changes to the layout at the beginning of the program
  - Evaluation of Split Case concept with supporting FEA (simplify assembly and disassembly procedure)
  - Updating of Diffuser Flowpath to reduce pressure drop and determine if additional axial or radial span is required (improve efficiency)
  - Updated rotor model with new axial span and decreased hub diameter
  - Attachment methods for internal hot components
  - Move most connections to the bottom half of the case
- At the end of BP1, the team will host a Conceptual Design Review to look over the design and provide necessary action items that will need to be addressed in BP2

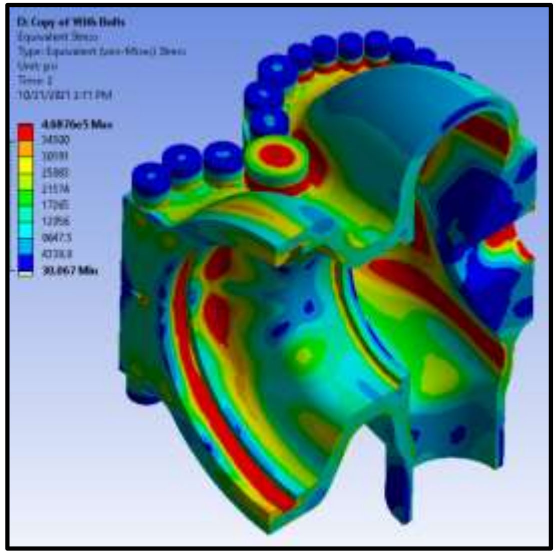


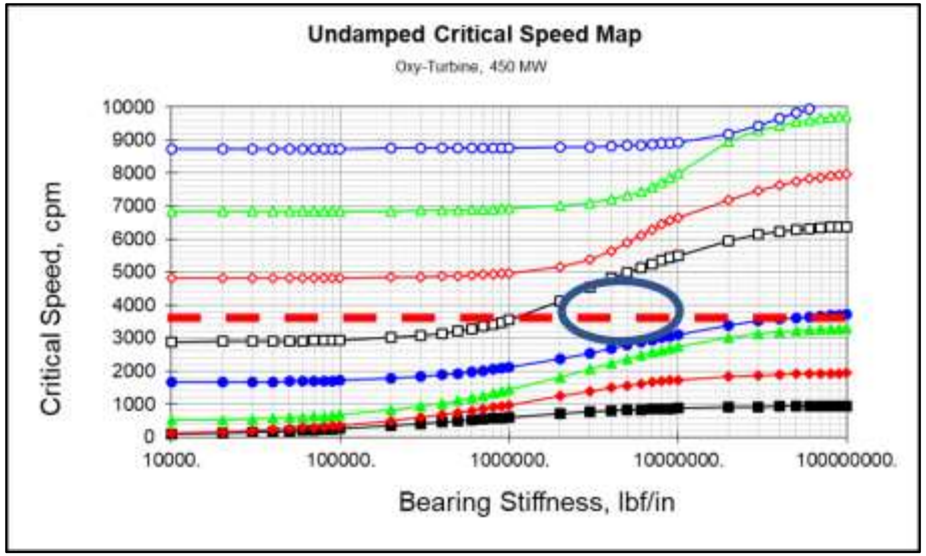


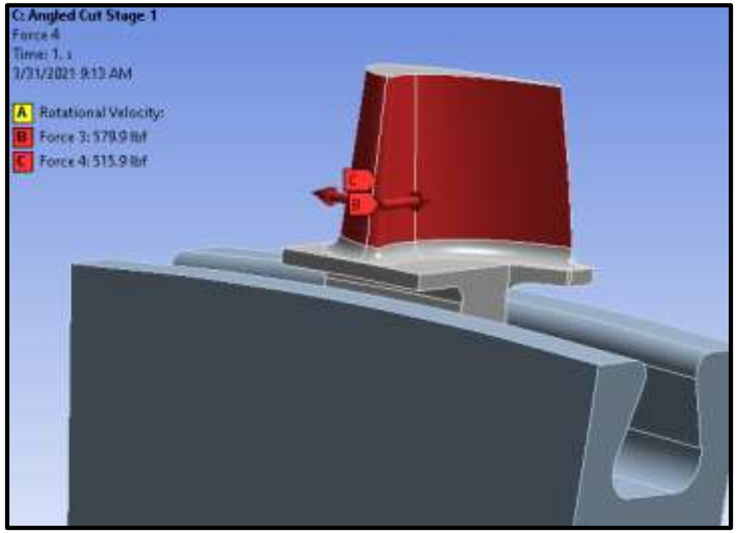
# Task 1.4 – Turbine Conceptual Design

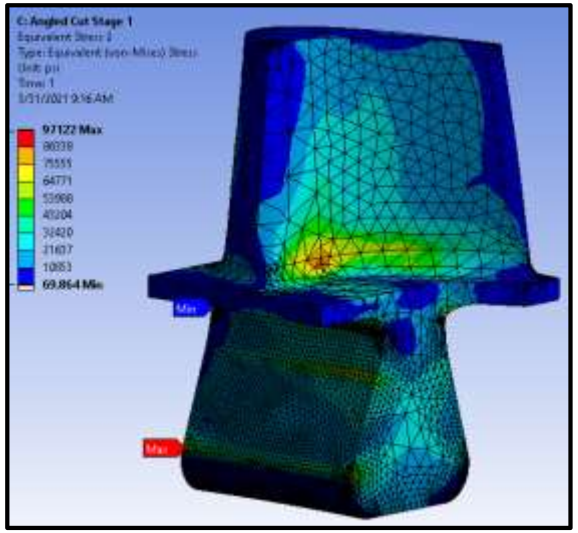


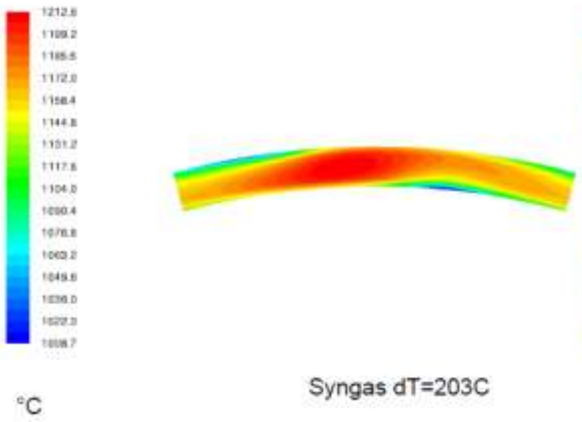


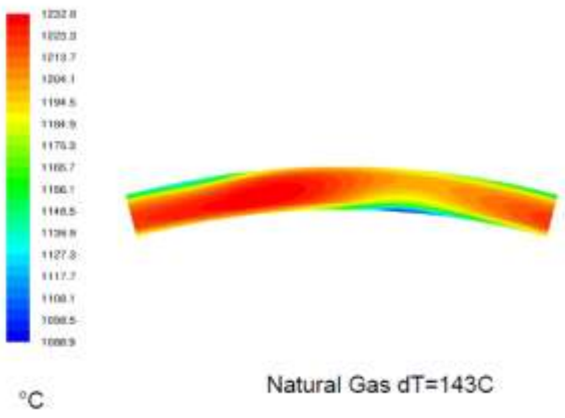



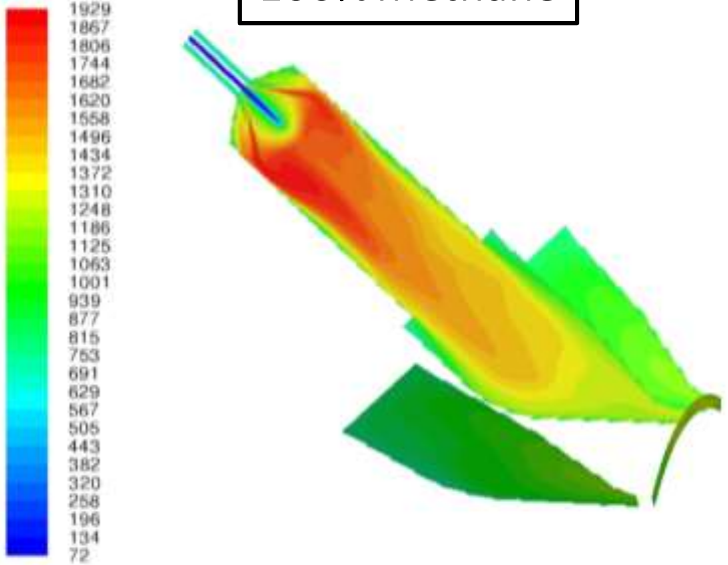
# Task 1.5 – Combustor Conceptual Design

- Syngas requires more fuel (mass flow) and less oxygen (mass flow). This leads to different flow velocity if using the same nozzle as a 100% $CH_4$ design
- With matching nozzles, the flame is moved far outside the can and is not properly attached. This leads to incomplete combustion and larger variation in properties at firing plane
- Velocities will have to be slowed down through the mixing of $CO_2$ in the fuel and oxygen flows upstream of the combustor can
- With same velocities, syngas will have a temperature spread around 60ºC higher than 100% methane (open annulus)

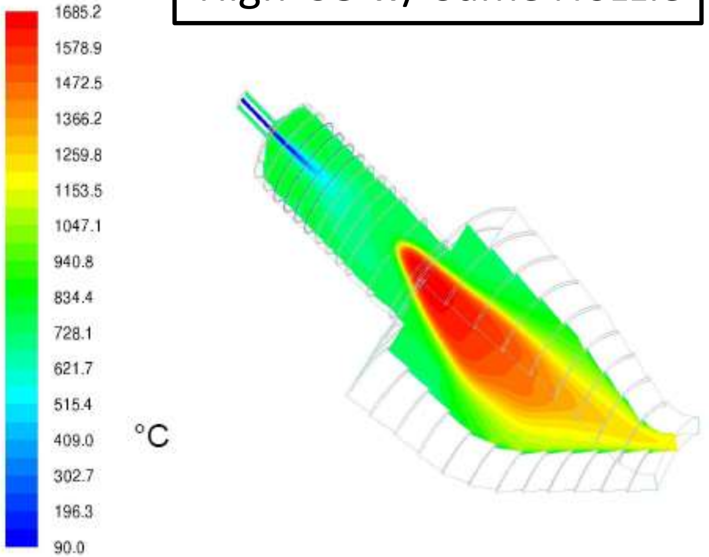


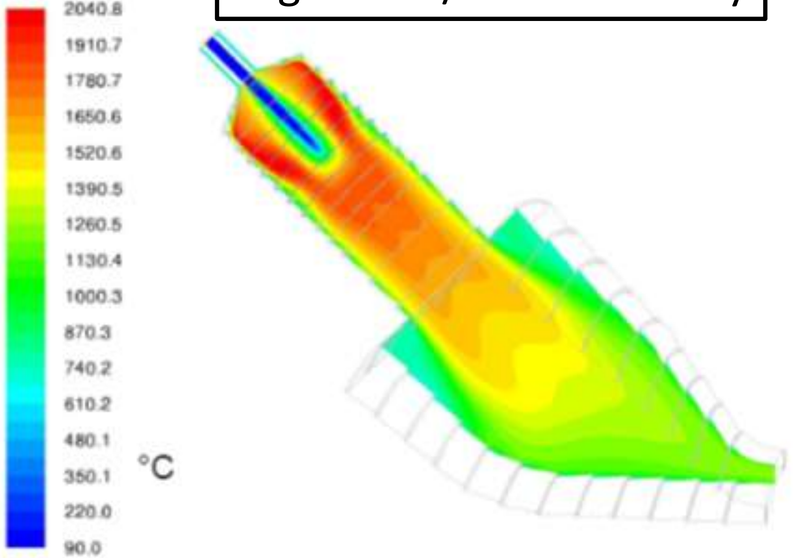

100% Methane




High-CO w/ Same Nozzle

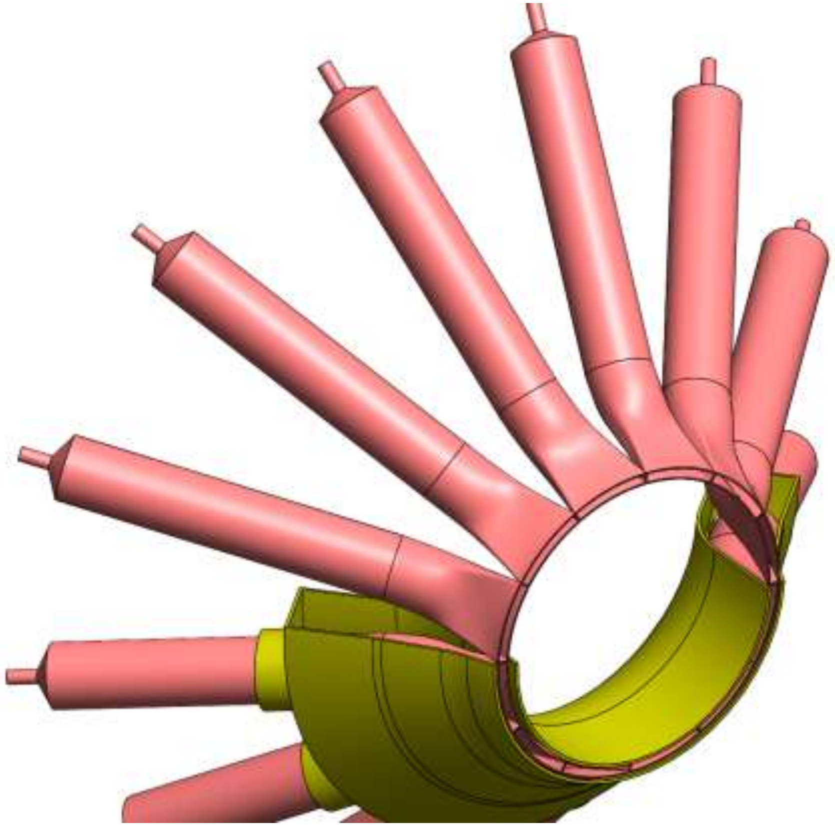


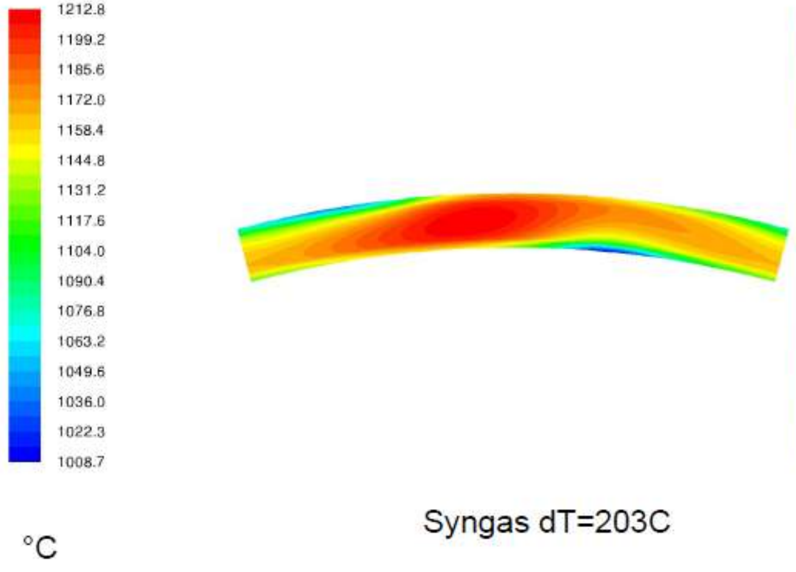

High-CO w/ Same Velocity



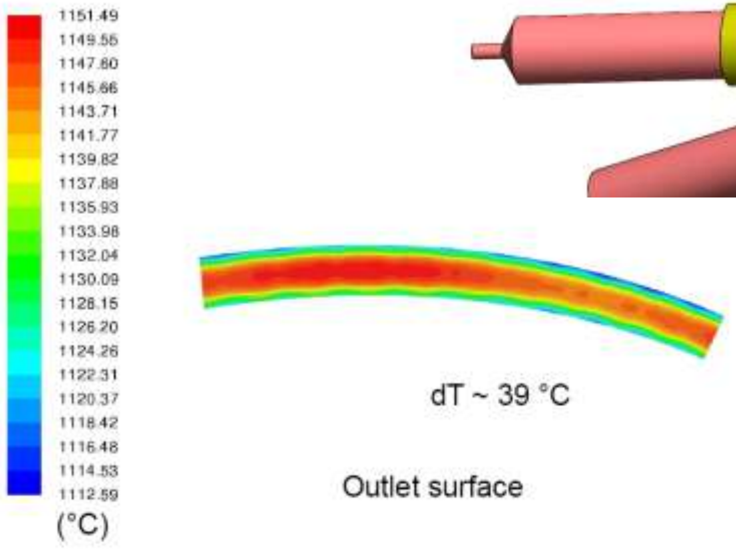
# Task 1.5 – Combustor Conceptual Design

- It was determined that the Combustor model should include stator vanes to look at impact on temperature distribution
- Stator Vanes provide a significant flow resistance (~40 bar pressure drop) and lessen the temperature distribution by 164°C
- Mass averaged temperature is currently around 1140°C. Will need to adjust fuel and recycle flows to reach 1150°C average temperature entering the stator vanes






Syngas dT=203C



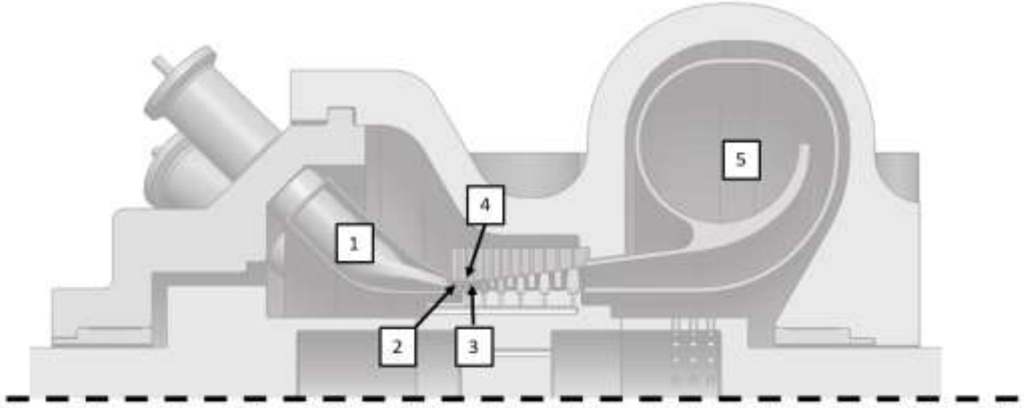

Outlet surface

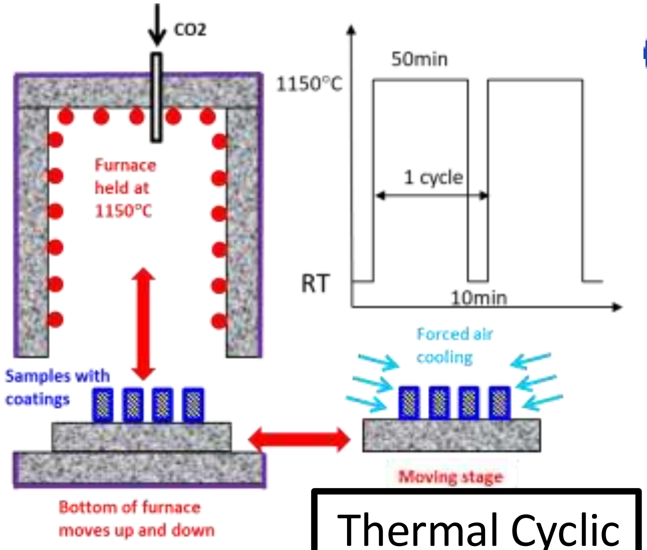
# Task 1.6 – Material Testing

## Task 1.6.1 – Material Selection

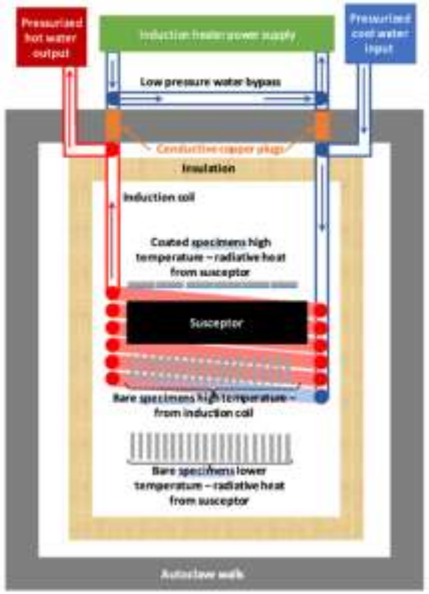
- Initial Material work was focused on establishing a baseline list of materials that could potentially be used in this turbine based on previous research and published data
- This required an initial understanding of where these materials would be used and what kind of conditions they would be seeing
- The primary areas are: Combustor liner, 1st stage vane, 1st stage blade, 1st stage blade tip, and exhaust plenum
  - If using an unshrouded blade design, the blade tip will not be coated with a TBC and will be exposed to much hotter temperatures while seeing much lower stresses
- All areas are exposed to the hot combustion flow with syngas byproducts
- All other areas of the turbine will be seeing clean, cooler, recycled $CO_2$ flow and will be buffered

| | Location | Temperature (°C) | Pressure (bar) | Mechanical requirements | Coatings |
|---|---|---|---|---|---|
| 1 | Combustor liner | 980 | 305 | Standard | Yes |
| 2 | 1st stage vane | 1150 | 305 | Standard | Yes |
| 3 | 1st stage blade | 1100 | 256 | High strength | Yes |
| 4 | 1st stage blade tip | 1100 | 256 | High strength | No |
| 5 | Turbine exhaust plenum | 764 | 30 | Standard | No |




Thermal Cyclic




High-Temp Autoclave

# Summary – Key Decisions

- To have an effective co-fired system between Natural Gas and Syngas, the combustor fuel & oxygen nozzles will require mixing flow from Recycled $CO_2$ or lower temperature sources to control flow velocity into the combustor
- Turbine can be designed for steady inlet conditions: Volume Flow, Temperature, and Pressure
- For better heat transfer assessment, the team will design a serpentine style test section to reduce measurement error and better mimic blade internals
- The blades will be designed to be manufactured through AM technology and will include heat transfer enhancements through pin-fins near the TE and impingement cooling on the LE. This will require a detailed understanding of limits through AM and also other manufacturing methods as back up
- For the 300 MWe 21$^{st}$ Century Power Plant, the team has chosen a 6 Stage Axial Turbine that is optimal from a cost, performance, and mechanical perspective
- Unshrouded and Shrouded Blade designs will be explored. While not typical the 1$^{st}$ stage of gas turbines, there is a chance that shrouded blades could be effective for the 1$^{st}$ stage of this turbine
- Labyrinth seals will be sufficient for the current target end seals. Hole pattern seals will be required for the balance piston
- The team is pursuing a horizontally split-case design to improve on turbine maintenance
- The turbine can be directly coupled to a generator without the need for a flexible coupling
- Turbine blades can be attached with circumferential dove tails to simplify the turbine rotor and reduce manufacturing cost

# Questions?

# Introduction

Advantages of a direct-fired sCO2 power cycle

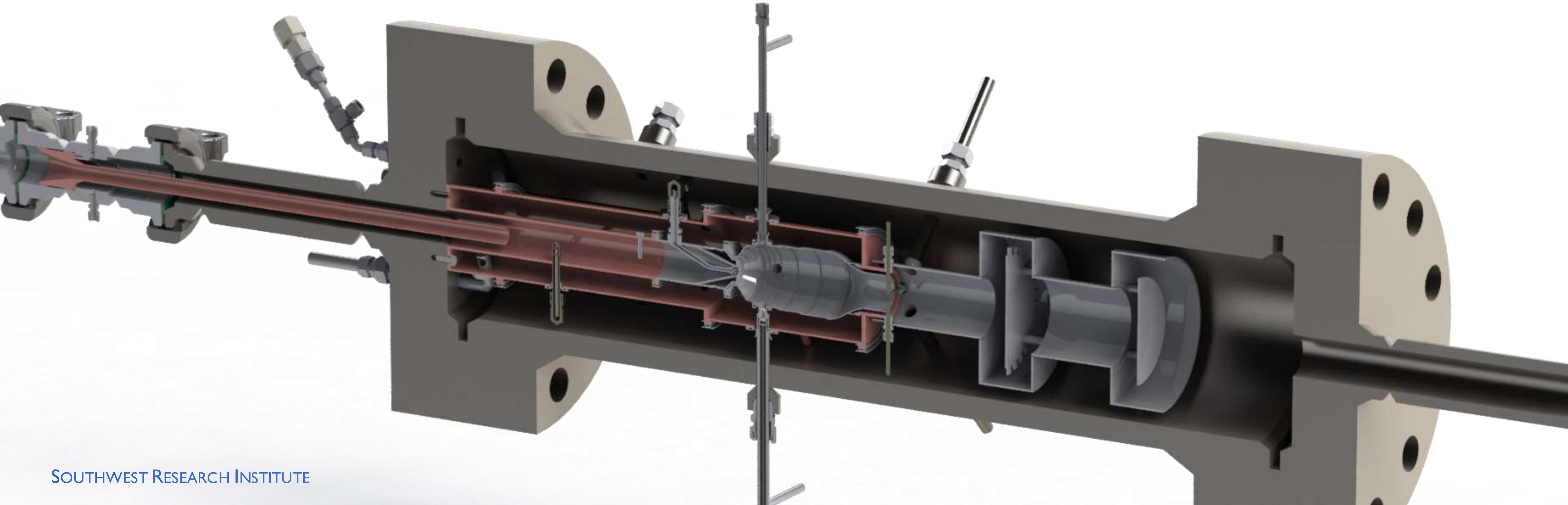
- Compact hardware
- Greater heat-addition efficiency
- Nearly 100% carbon capture

Challenges

- Lack of validated combustion modeling techniques
- High pressure and temperature

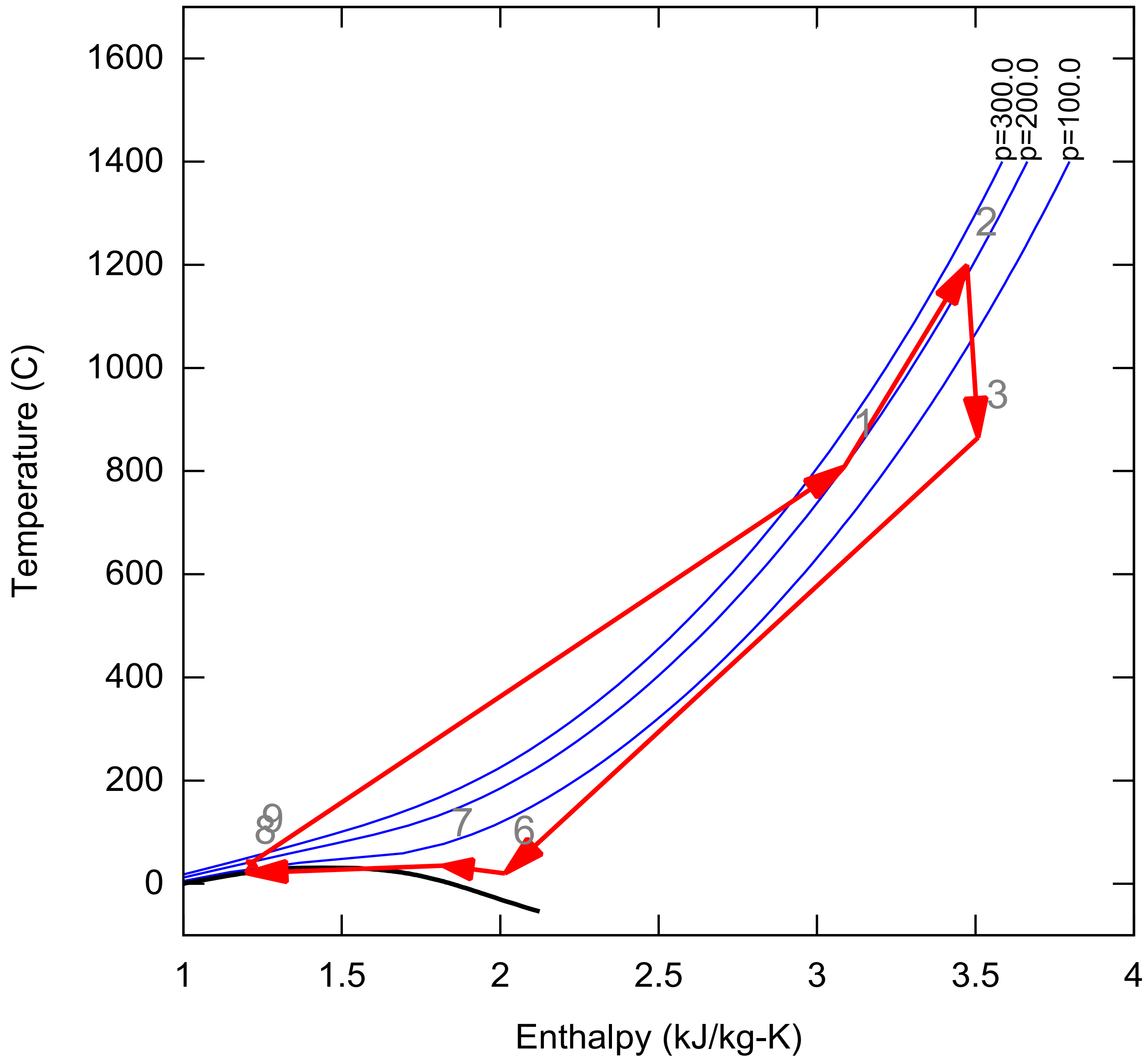
# Project Objectives

- 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 using optical access for advanced diagnostics

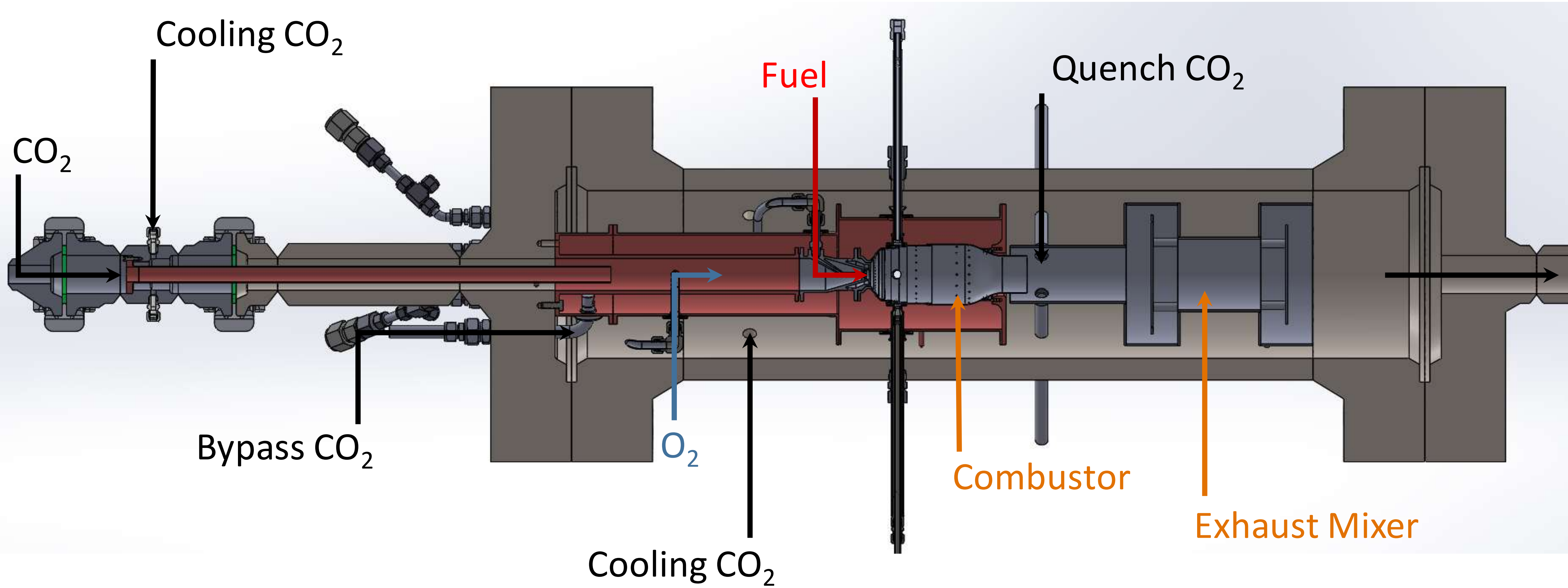


# Cycle Conditions

- Combustor Inlet and Outlet temperatures dictated by reviewing previous cycle modeling work done at SwRI
- Combustor inlet temperature: 700°C at 200 bar
- Combustor outlet temperature: 1200°C
- Achieves a plant efficiency comparable to a NGCC power plant

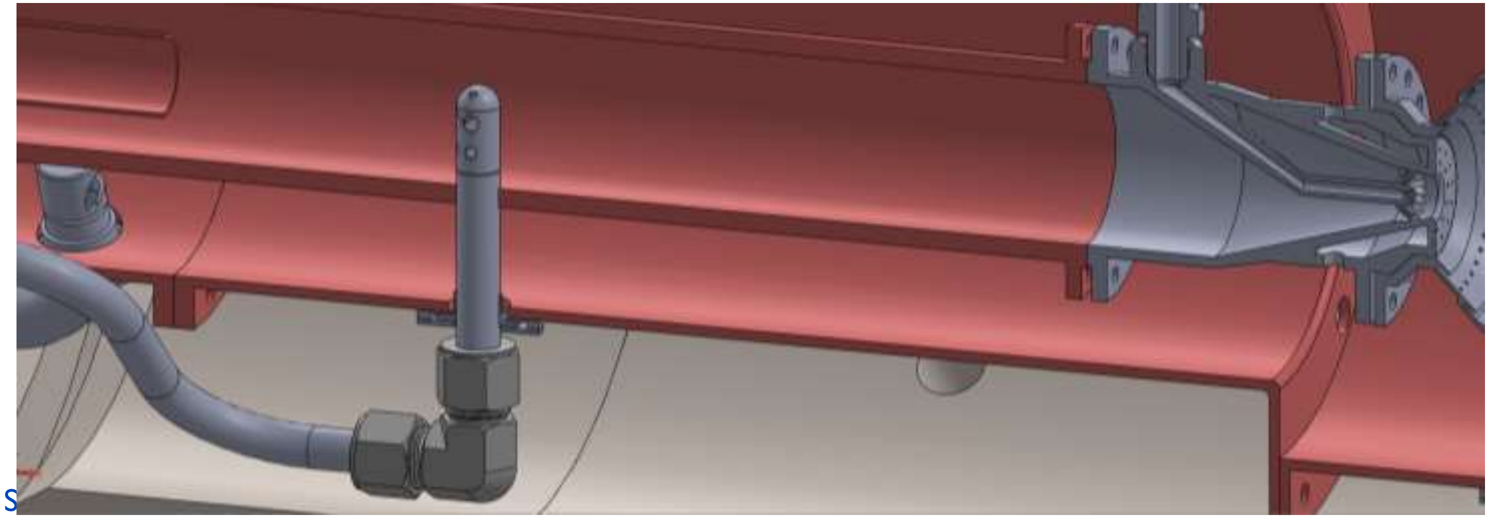


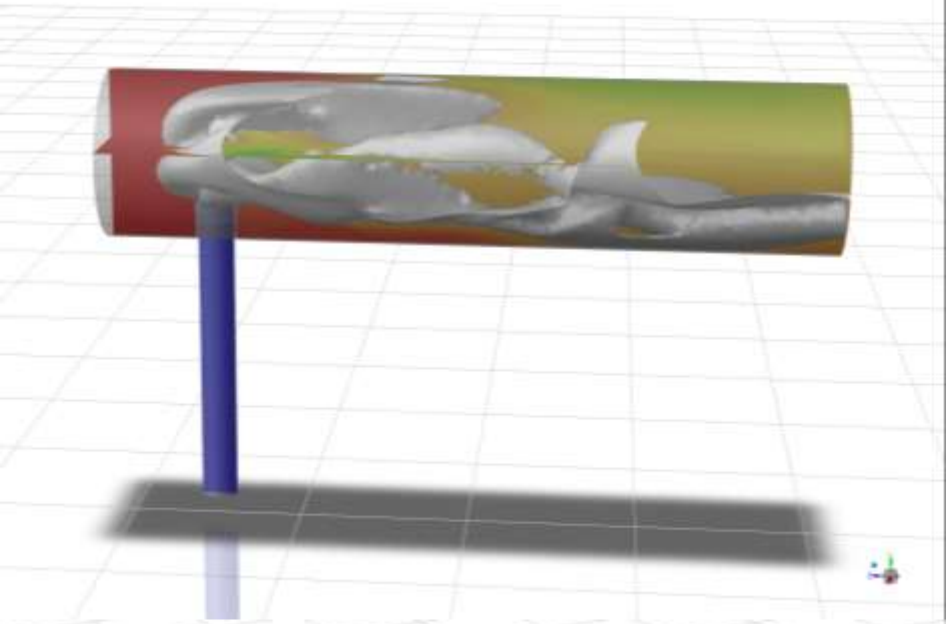
# Combustor Schematic

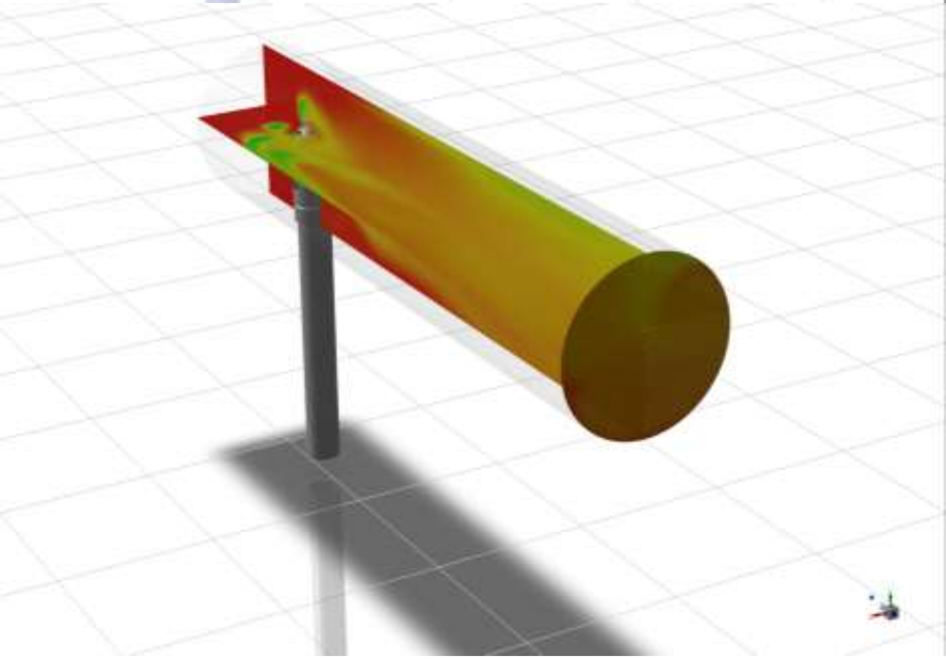


# Oxygen System

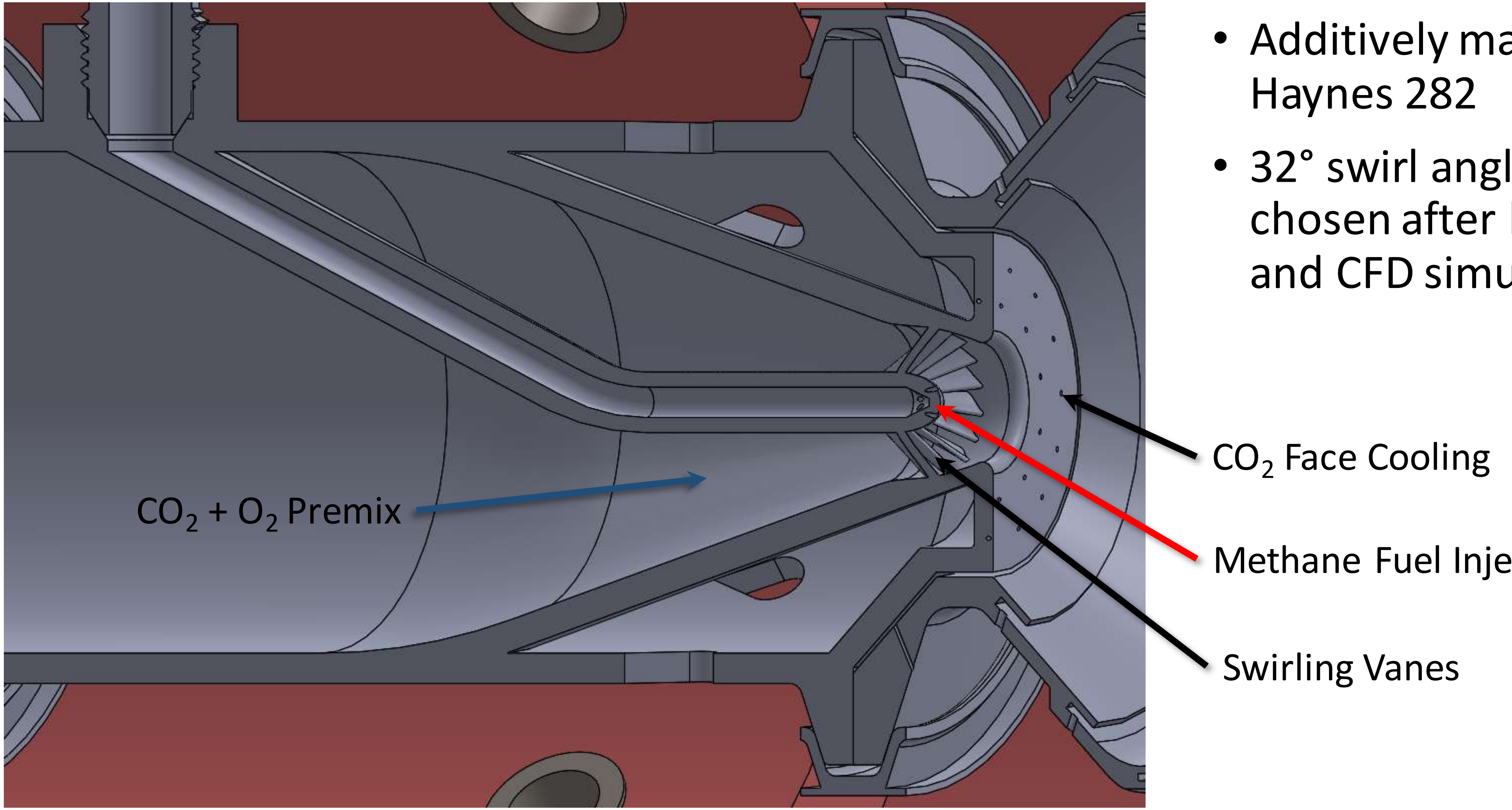
- Guidance from personnel at NASA Stennis and White Sands, review from project partner Air Liquide
- LOX tank with cryogenic pump and ambient vaporizer
- Oxygen injection upstream of fuel injector







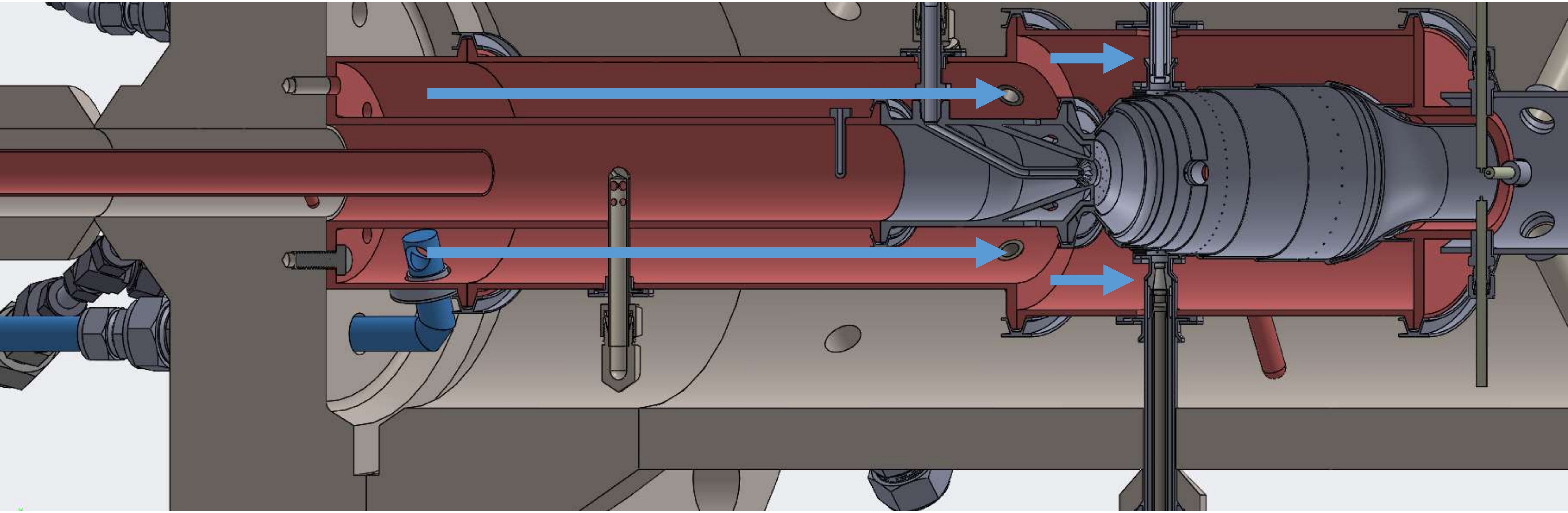
# Fuel Injector




- Additively manufactured Haynes 282
- 32° swirl angle of inlet vanes chosen after literature review and CFD simulations

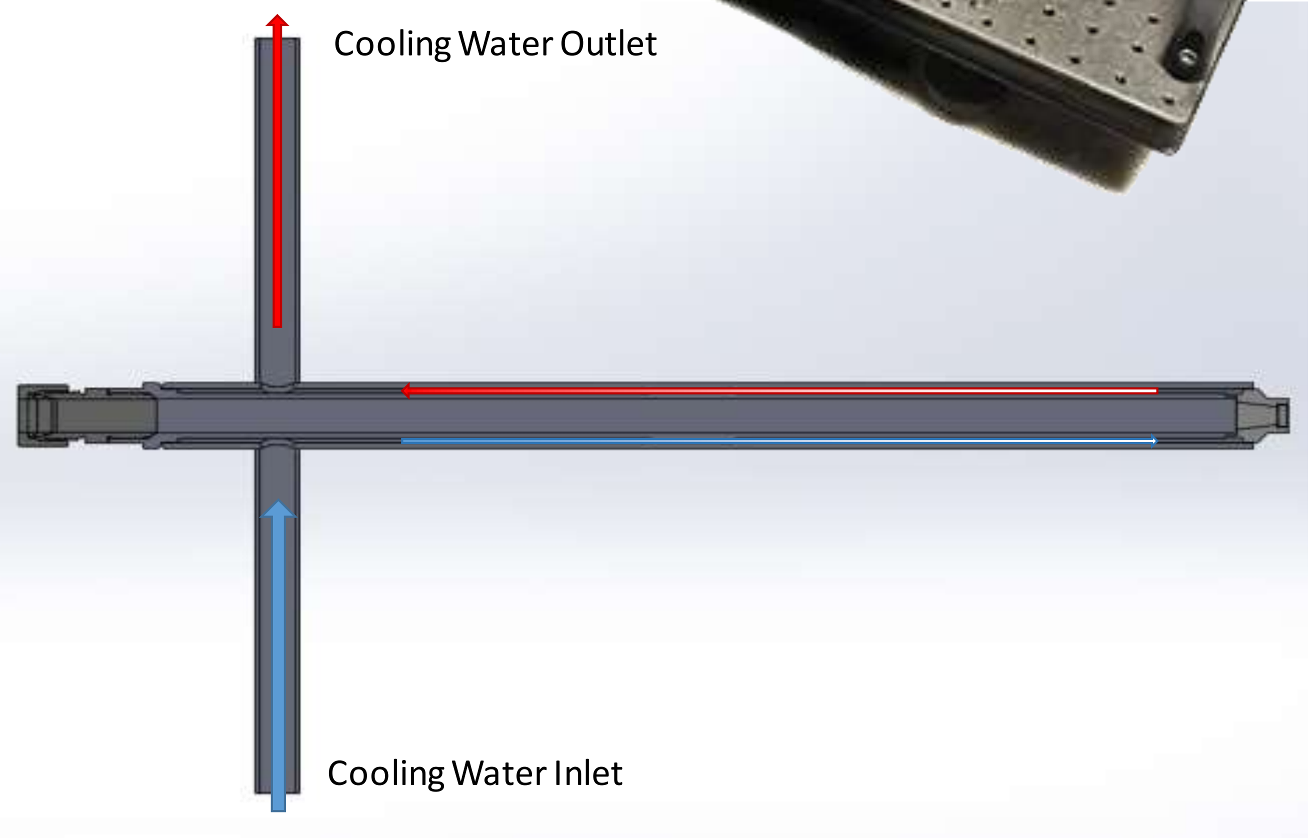
# Combustor Cooling

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

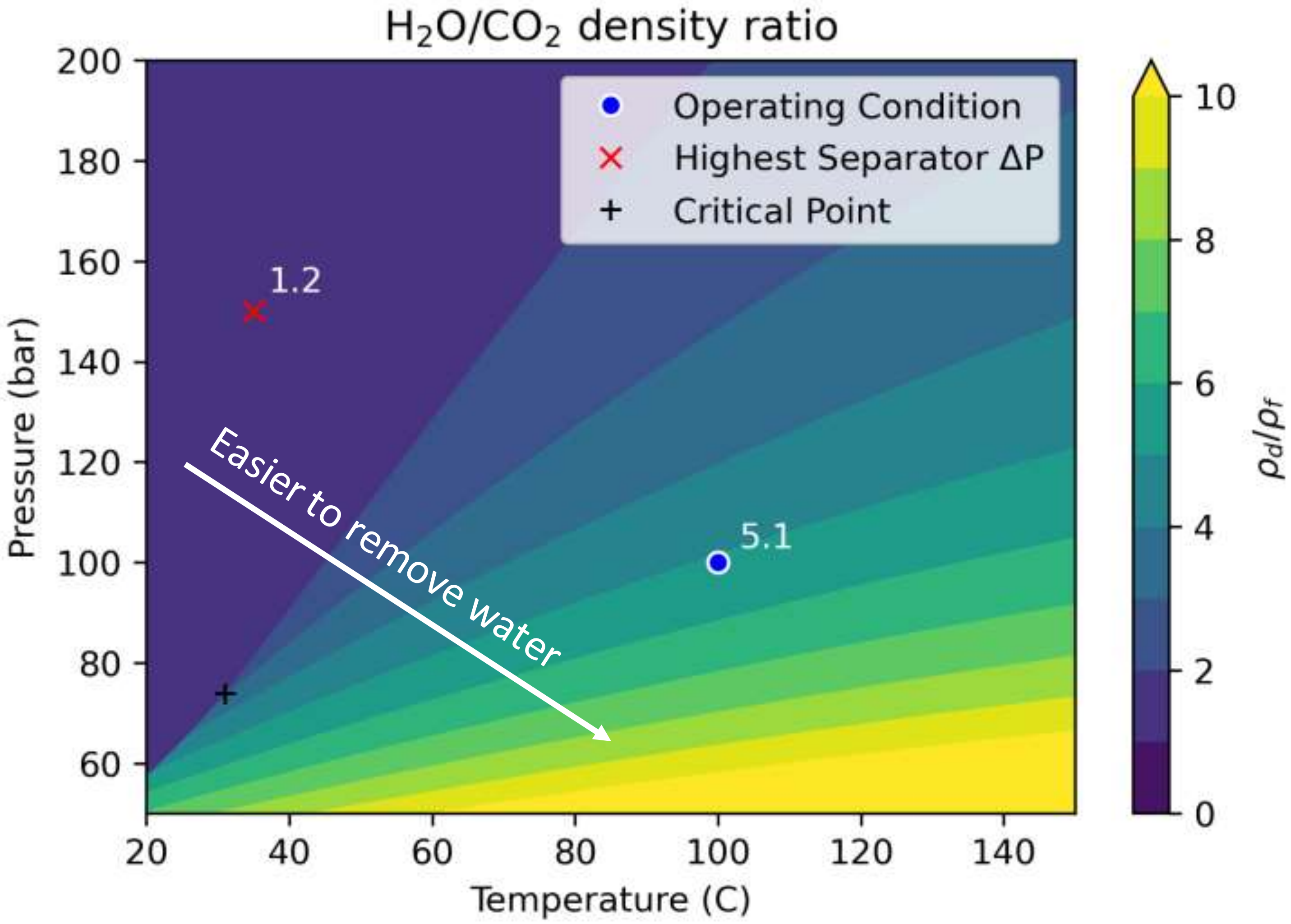


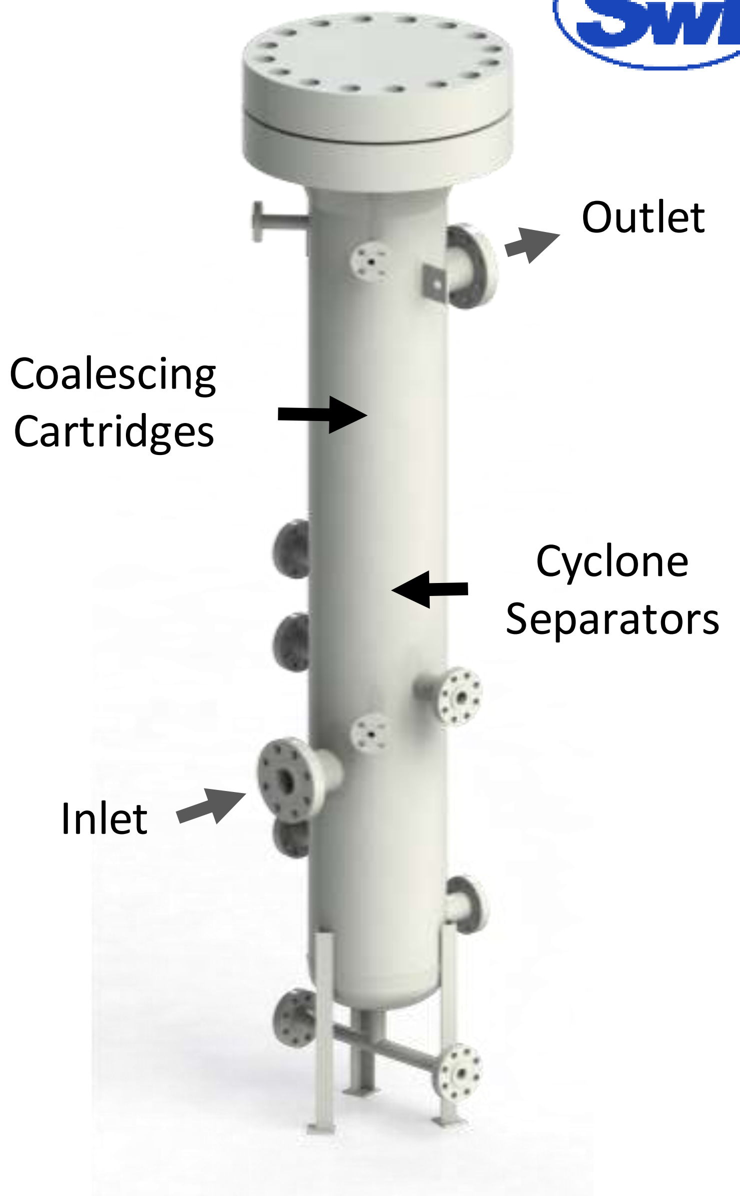
# Laser Ignition System

- Class 4 Quantel Qsmart Twins
  - 2x380mJ @ 532nm, 10Hz
- Water cooled probe allows access to the combustor and keeps focal lens temperature low

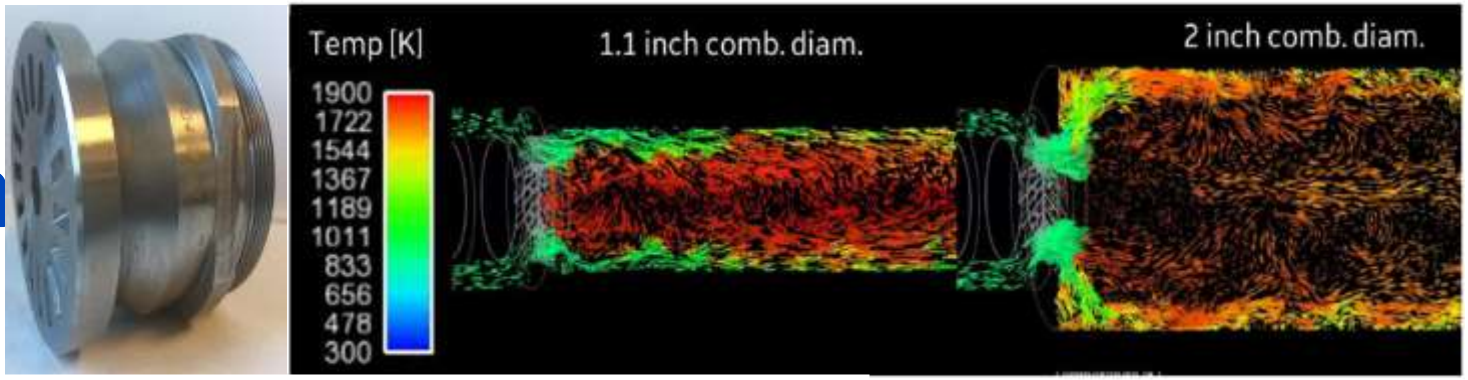



# Water Separator

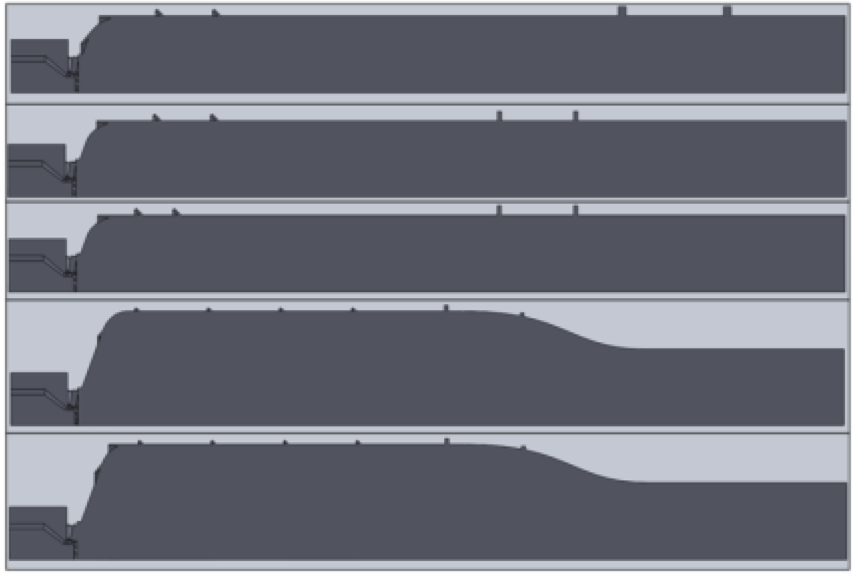


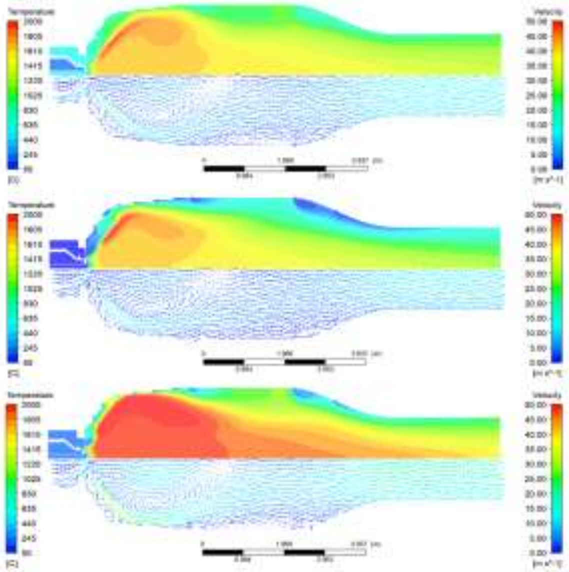



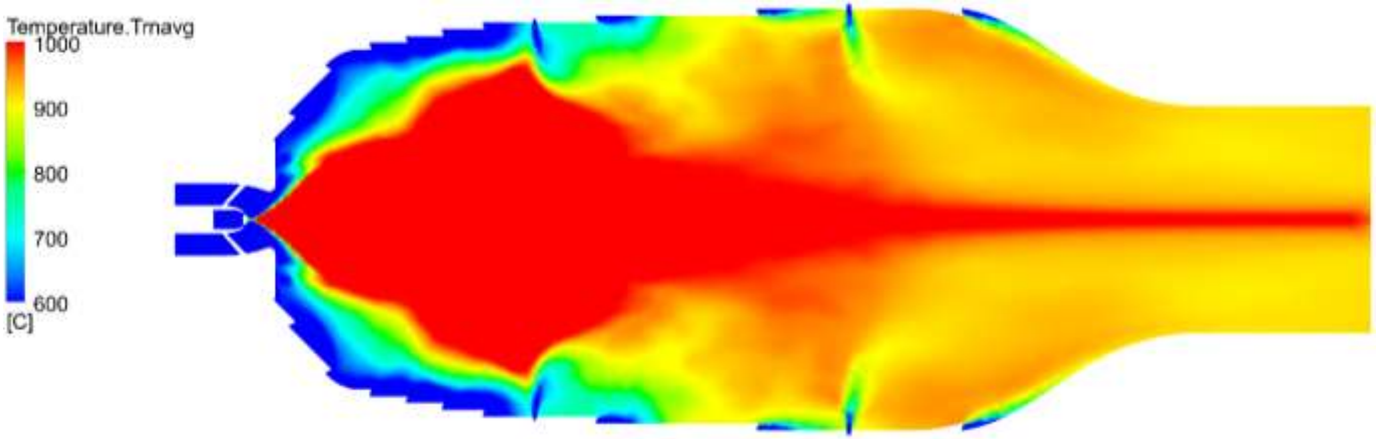
# Combustor Design




- Design work began in conjunction with GE-GRC using a heritage swirler
- Design maturation focused on flame holding and film cooling
- Final combustor design uses film cooling slots, recirculation holes and dilution holes

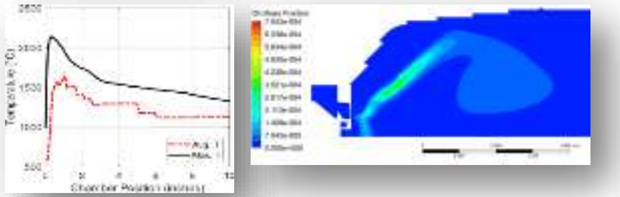




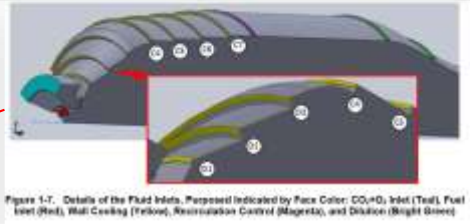


# CFD Design

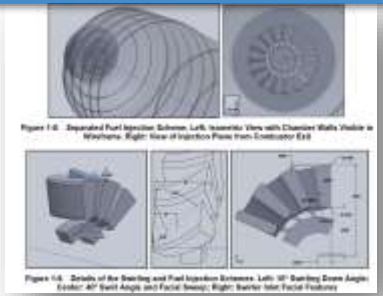
Heat Release And Flame Holding



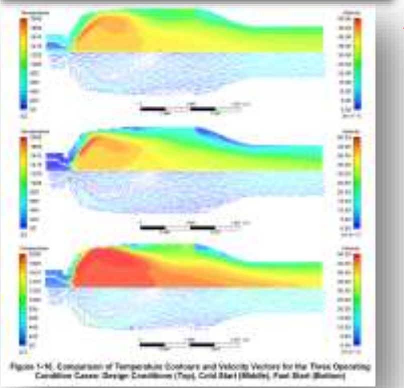
Cooling/Recirculation Schemes

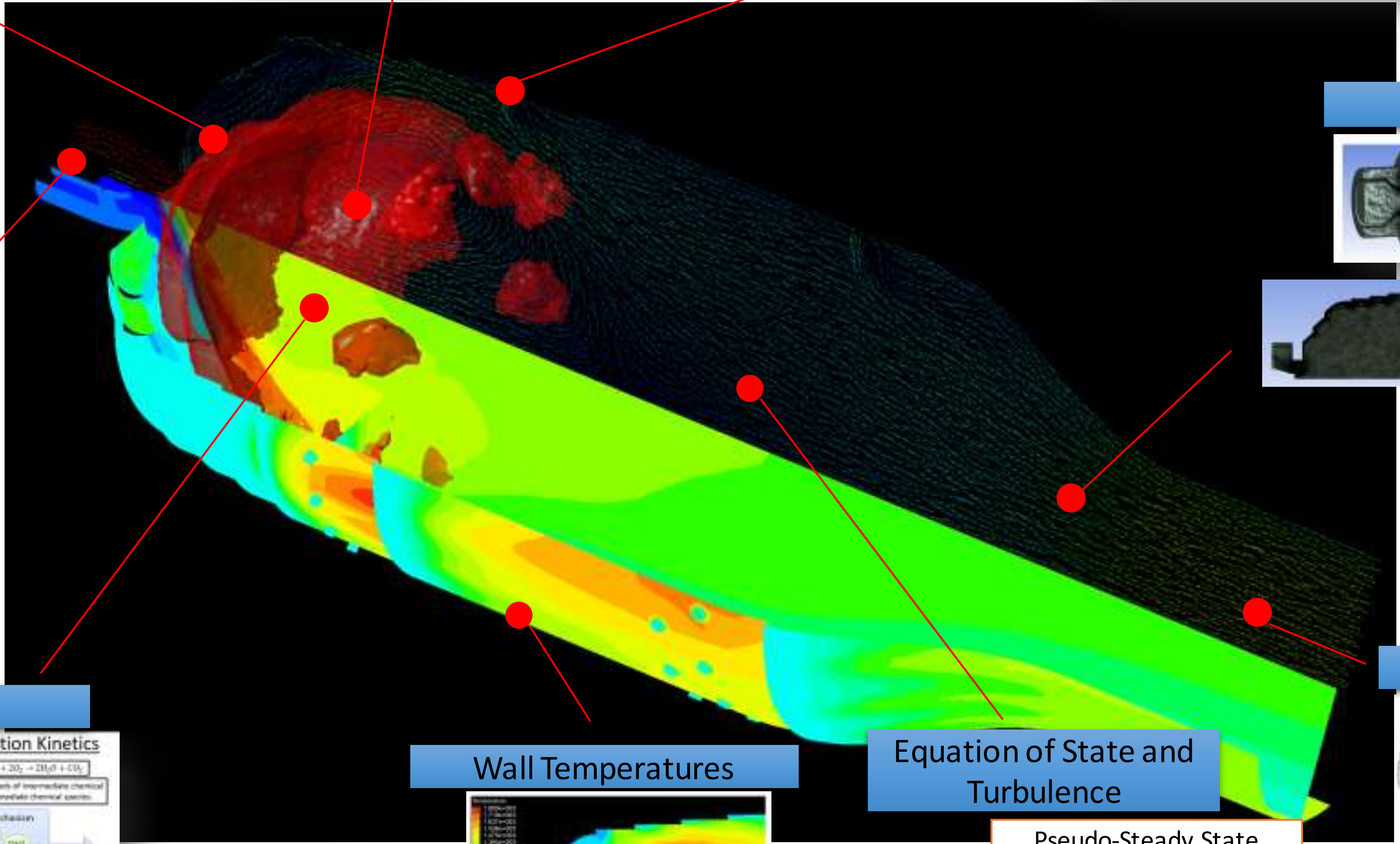


Injection and Swirl

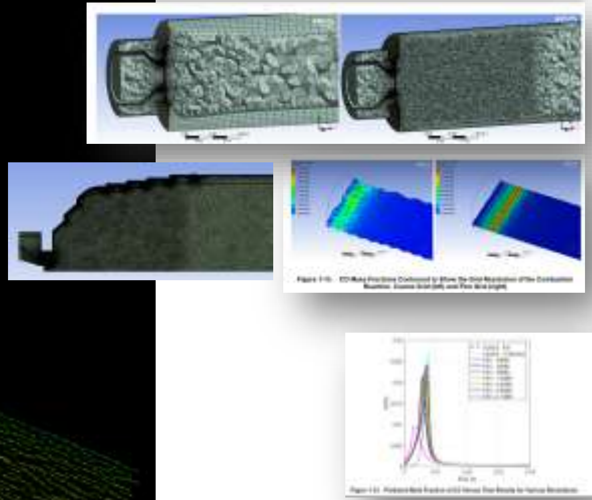


Startup Conditions

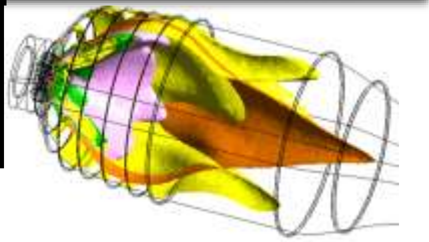




Mesh Sensitivity



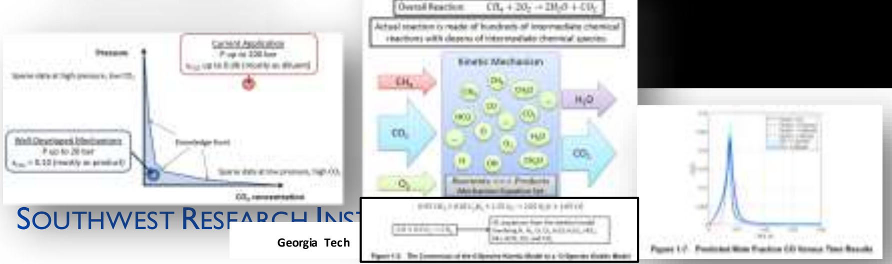
Unreacted Products



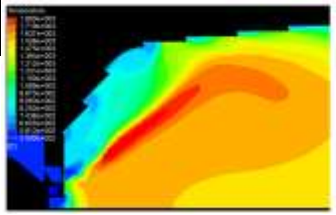
Chemical Kinetics

Kinetics Knowledge Base

Chemical Reaction Kinetics



Wall Temperatures



Equation of State and Turbulence

Pseudo-Steady State

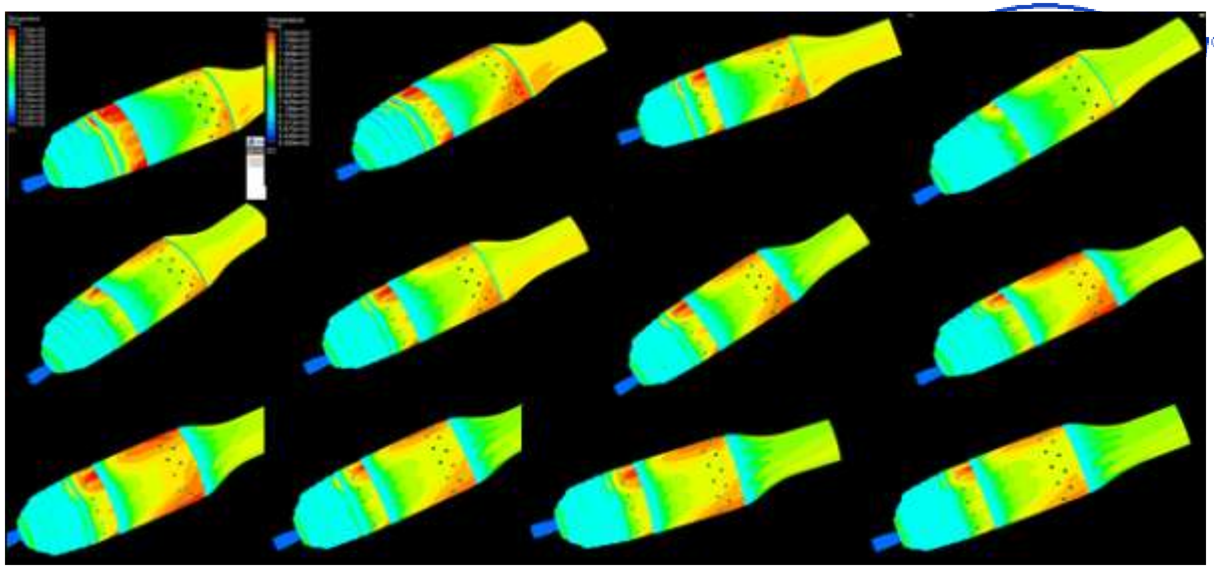
$k-\omega$ RANS

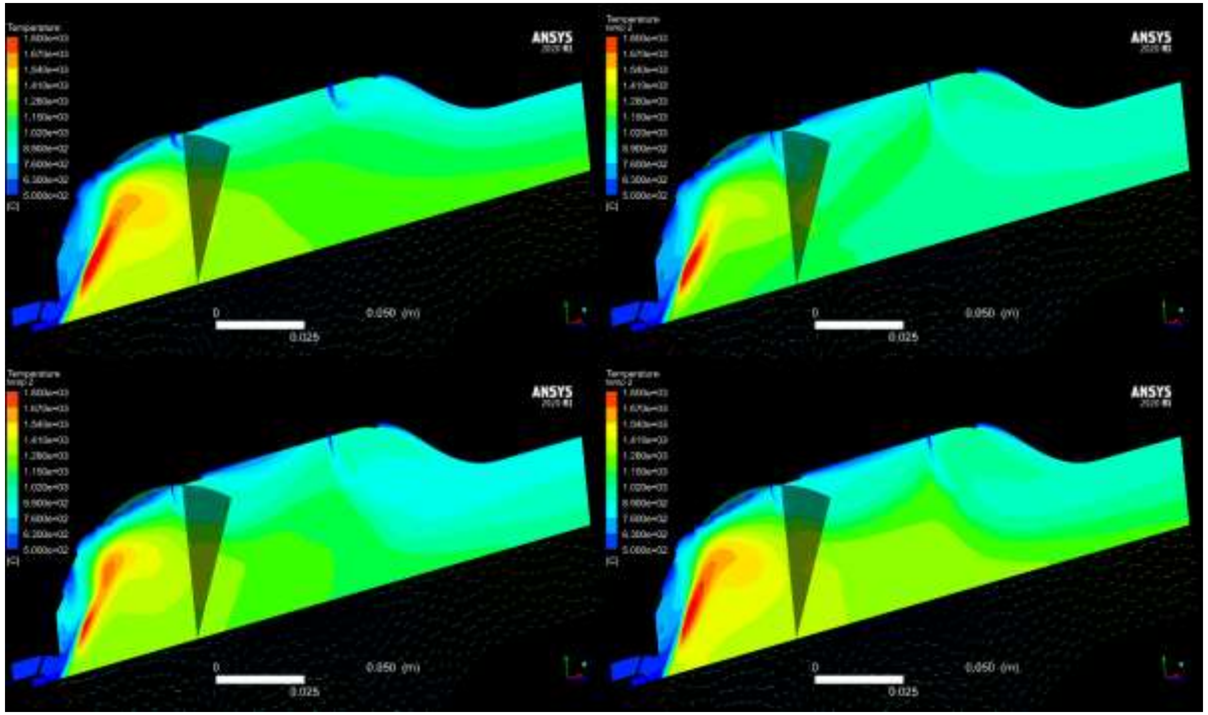
ANSYS FLUENT

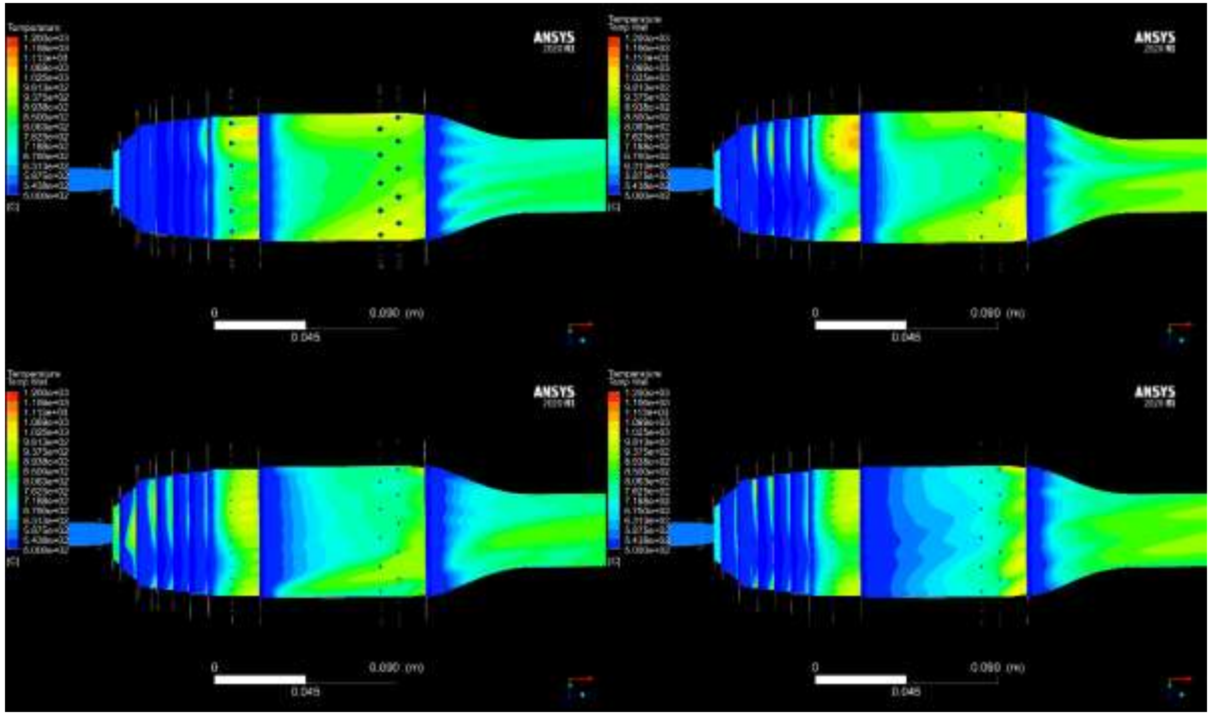
Ideal Gas vs Cubic EOS

# Combustor Design

- Recent work includes dozens of iterations to film cooling geometry to minimize hot spots



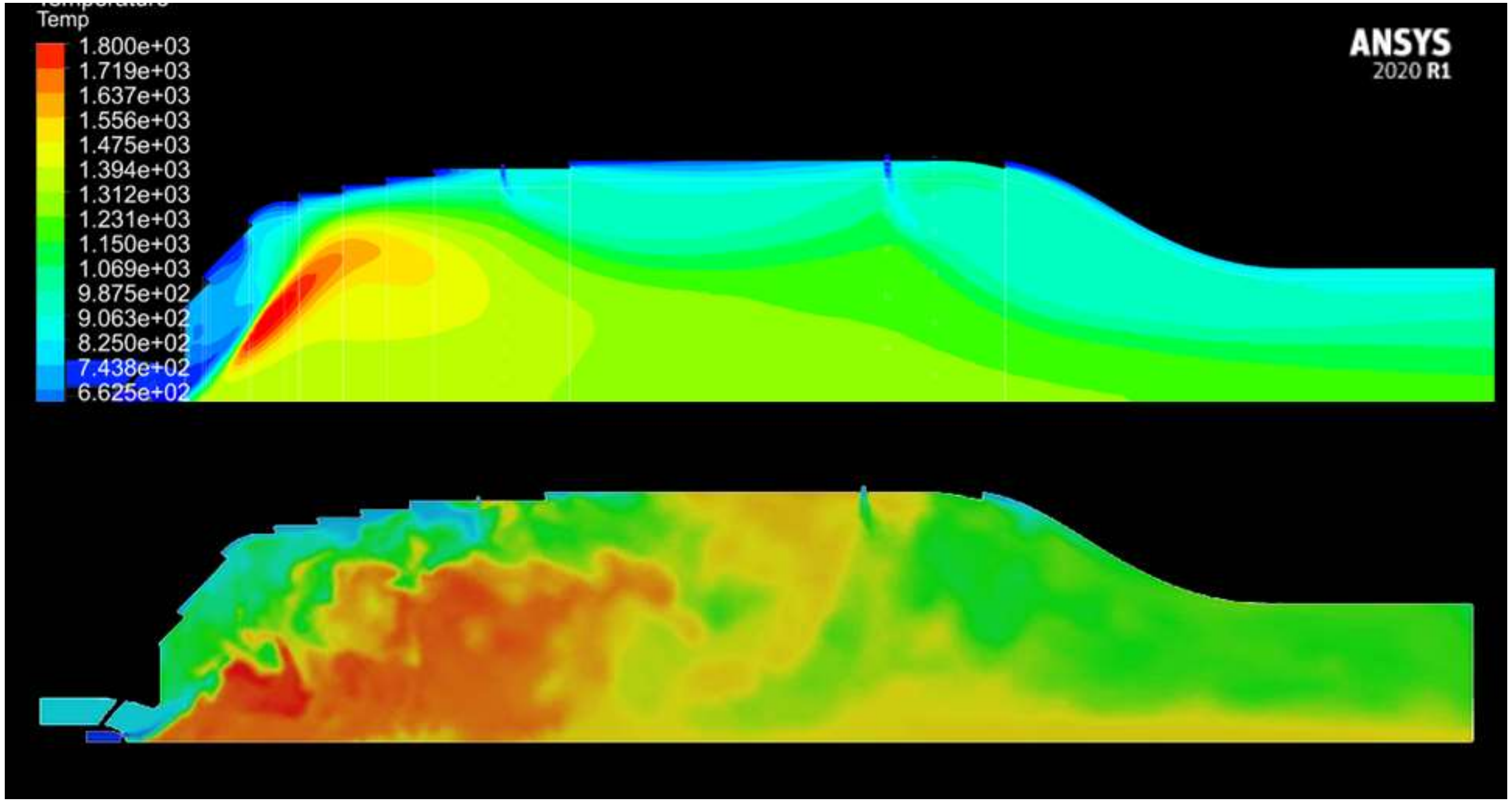


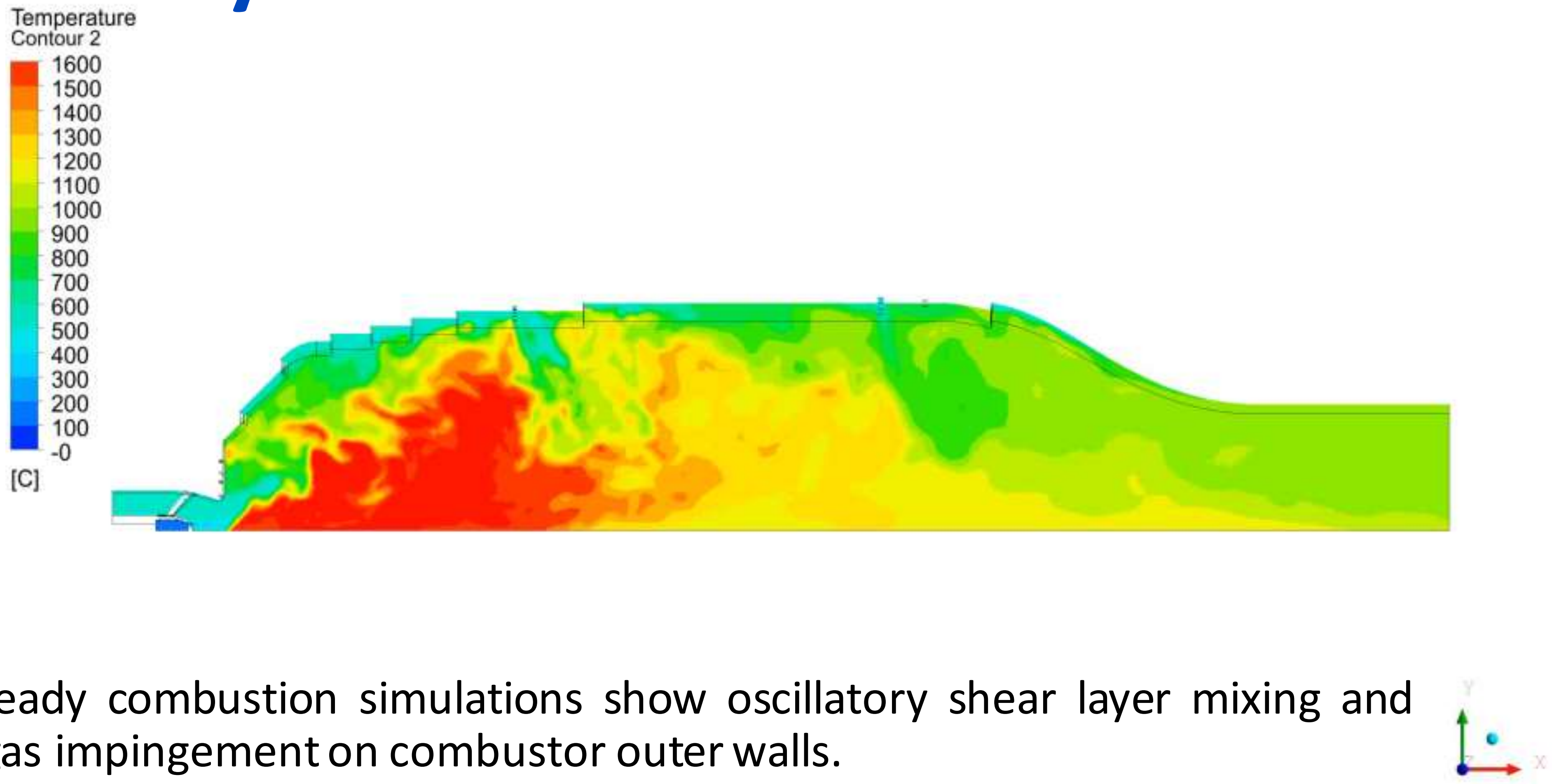
# Combustor Design

Steady RANS Simulation

Unsteady DDES Simulation

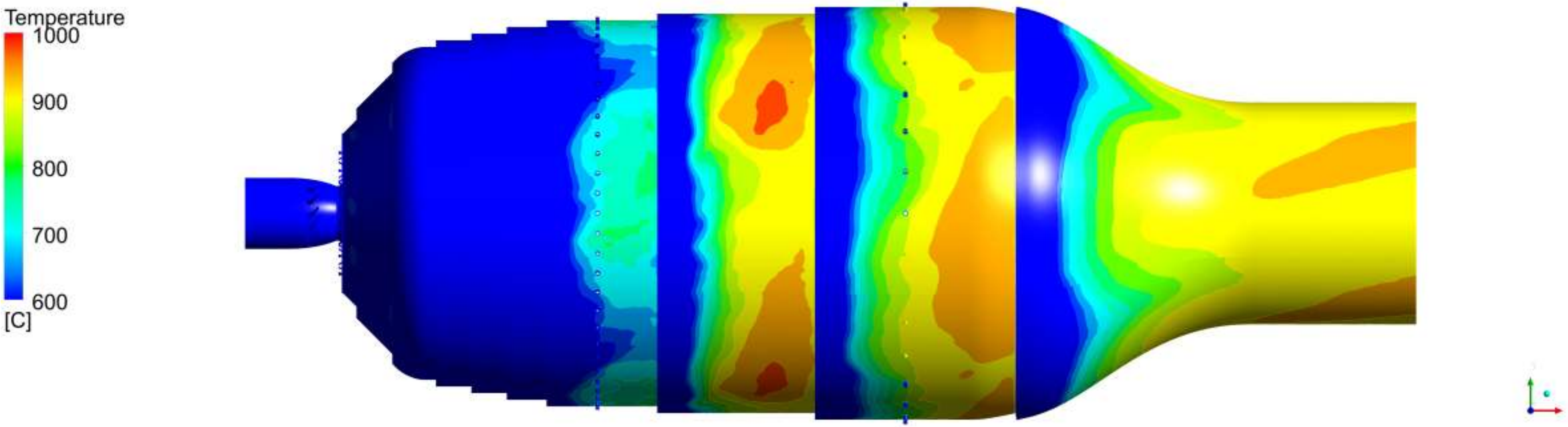


# Unsteady Combustion Simulations




Unsteady combustion simulations show oscillatory shear layer mixing and hot gas impingement on combustor outer walls.

# Notional Wall Temperatures




Adiabatic simulations suggest peak combustor wall temperatures near 1000 C, which will be decreased further with exterior cooling flows.

# Oxygen Storage Incorporated into the Allam Oxy-Fuel Power Cycle

Jeffrey Moore, Ph.D., SwRI

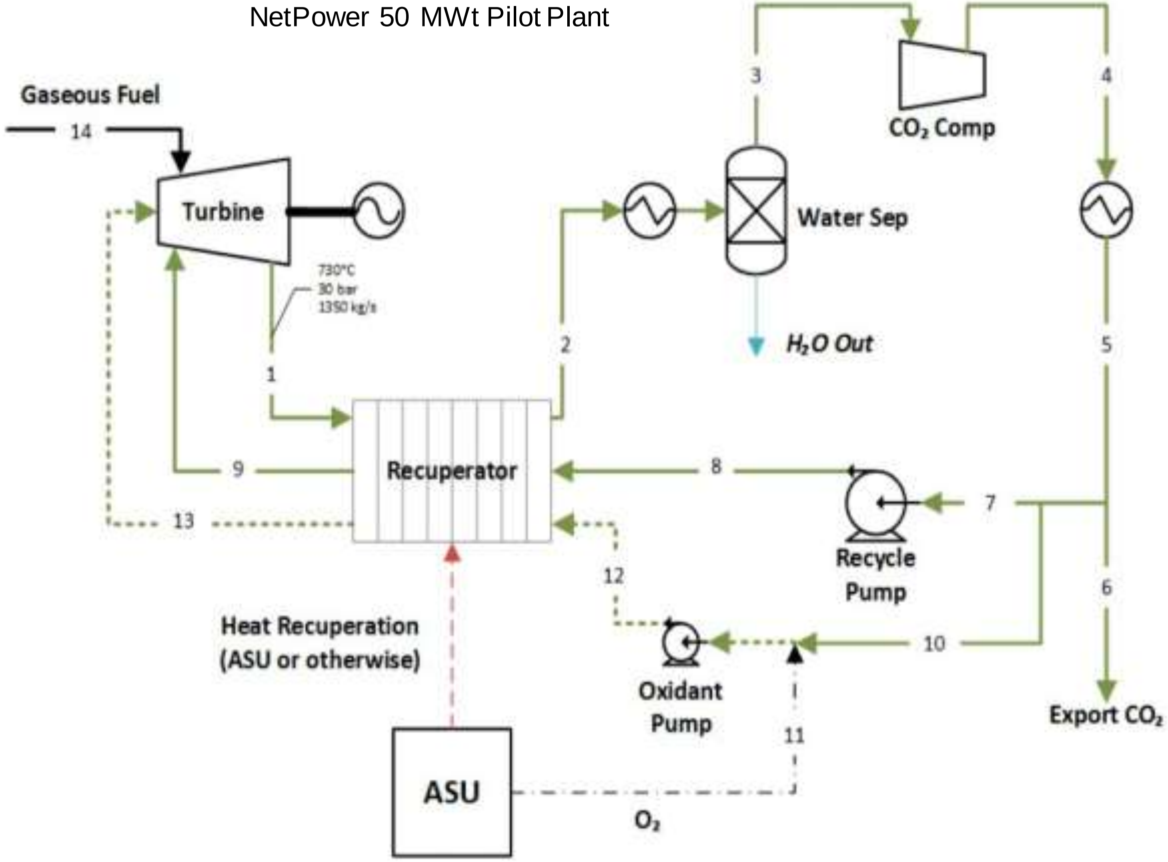
**Team Members:**
**8 Rivers Capital, LLC**
**Air Liquide**
**SoftInWay Inc.**


Supercritical carbon dioxide power plant with liquid oxygen storage to reduce capital costs and increase design flexibility

# The Concept

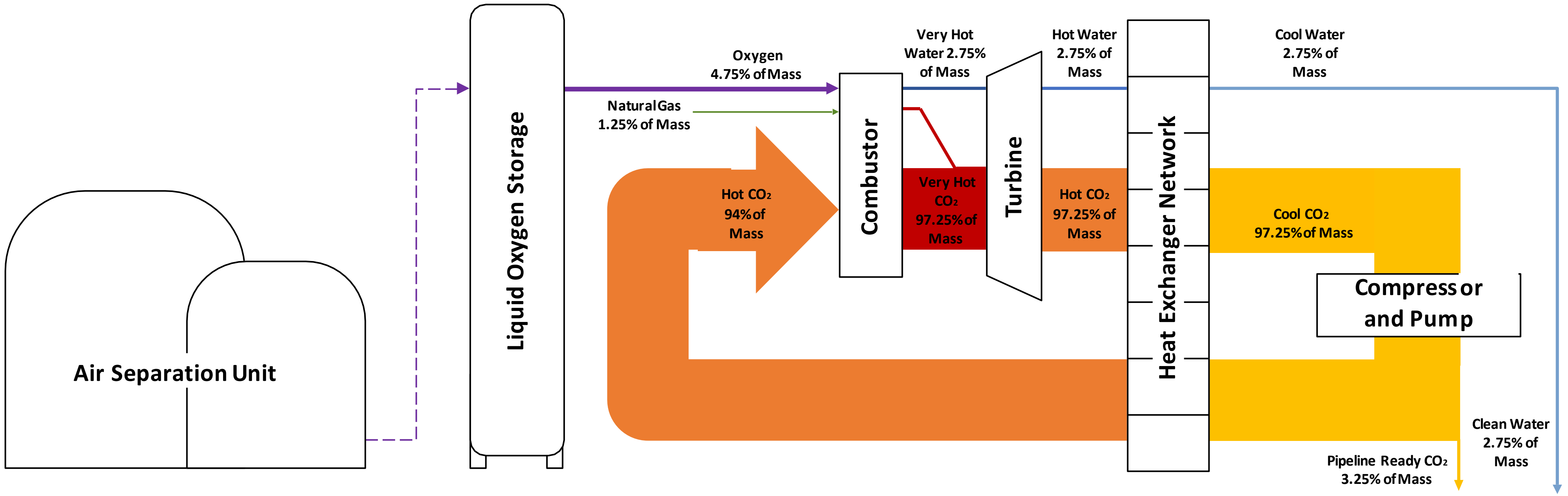
- The Allam-Fetvedt Cycle (AFC) is a highly-recuperated, oxy-combustion, semi-closed supercritical $CO_2$ cycle with inherent carbon capture and world-class thermodynamic efficiency
- $CO_2$ produced in the cycle is clean—free of harmful contaminants, e.g., NOx and SOx—and is available at pipeline or sequestration pressure for permanent storage

NetPower 50 MWt Pilot Plant



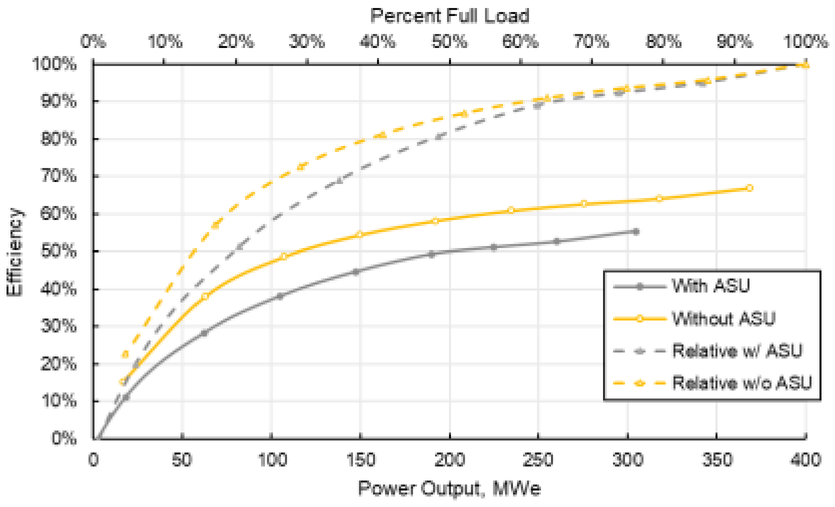
# The Concept

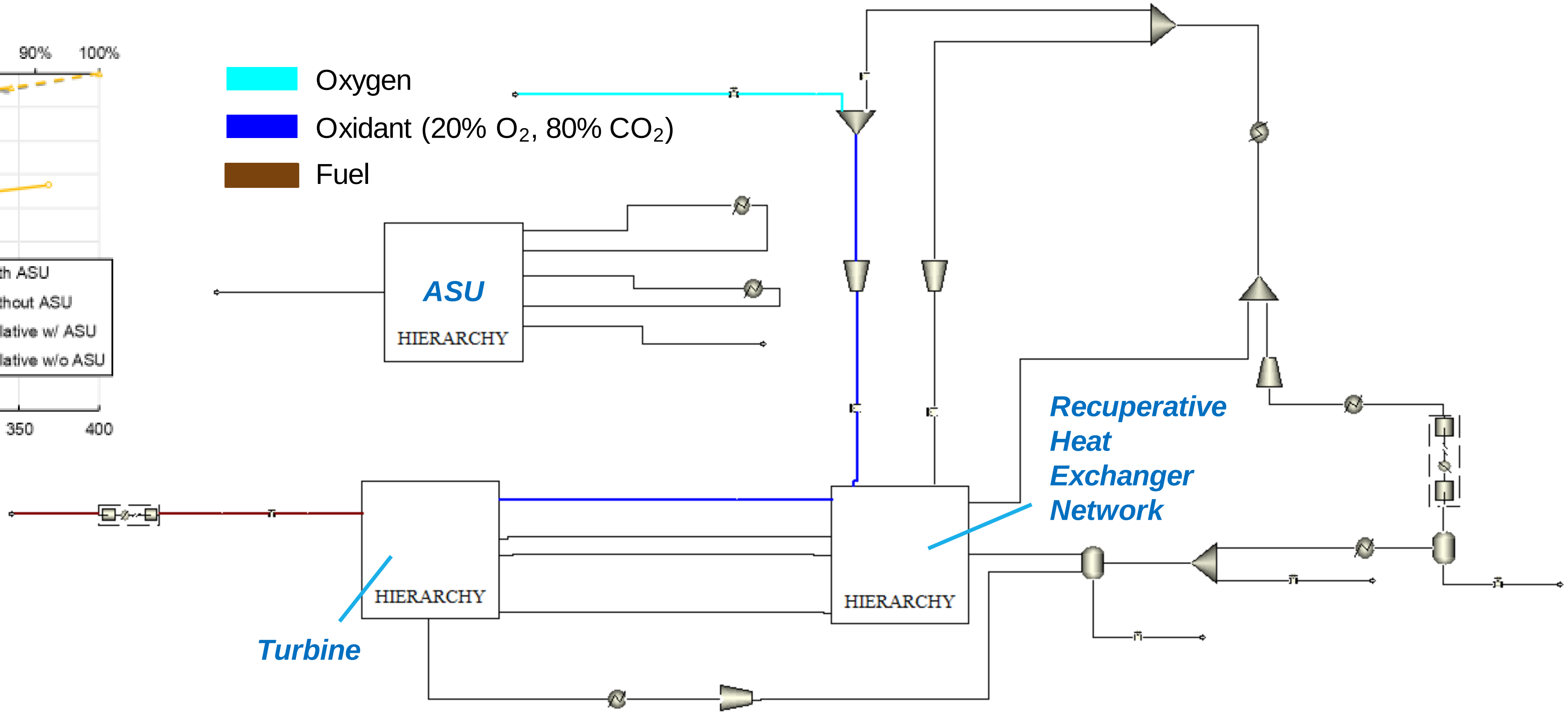
- Pairing liquid oxygen (LOX) storage with NET Power technology, the Allam- Fetvedt Cycle (AFC), allows energy utilities to take advantage of the price swings of electricity characteristic of future grids with high renewable resource penetration to produce zero-emissions power cheaply and on-demand
  - The AFC offers fast response times for exceptional load following and grid support capabilities



# The Concept

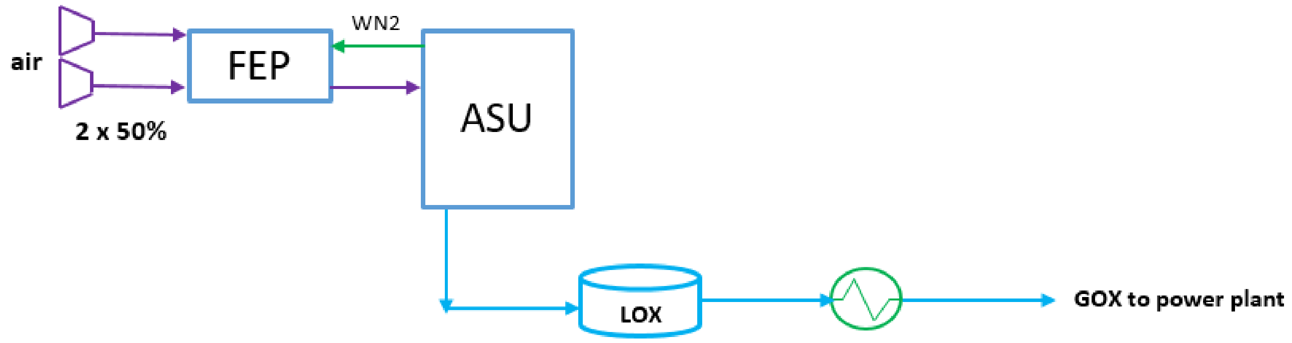
- Detailed process modeling results are coupled with an NPV-optimizing algorithm to determine the most economically favorable operating schemes for deployments in various regions of the future US electricity grid
  - LOX is produced & stored when electricity from the grid is cheap while power is produced when energy can be sold most profitably



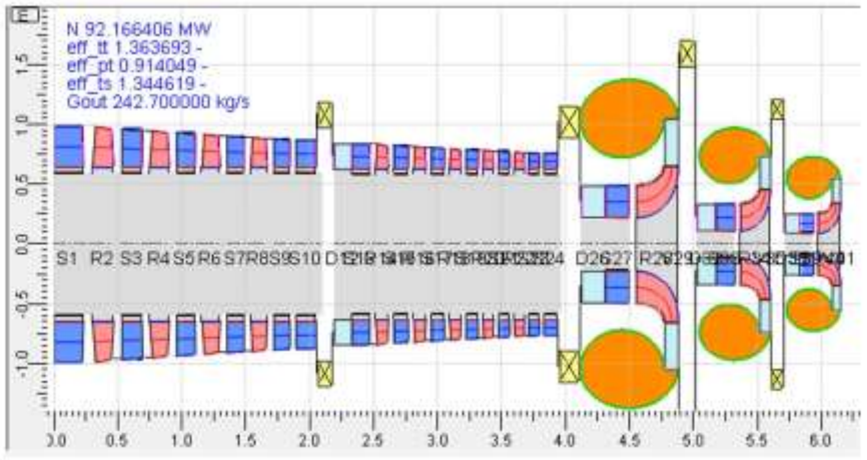



# ASU Process – ASU with Integrated Liquefaction

- Air Liquide designed ASU with integrated liquefaction was selected based on benchmarking several options with regard
- This option is expected to be lower CAPEX oriented as it contains less equipment
- The specific power per unit of LOX is on par with the previously studied design, or even a bit better
- Preliminary performance results:
  - The Expected ASU power consumption 99 MW in annual average conditions
  - US Gulf Coast basis for ambient conditions
  - Expected airflow 676,00 $Nm^3/h$

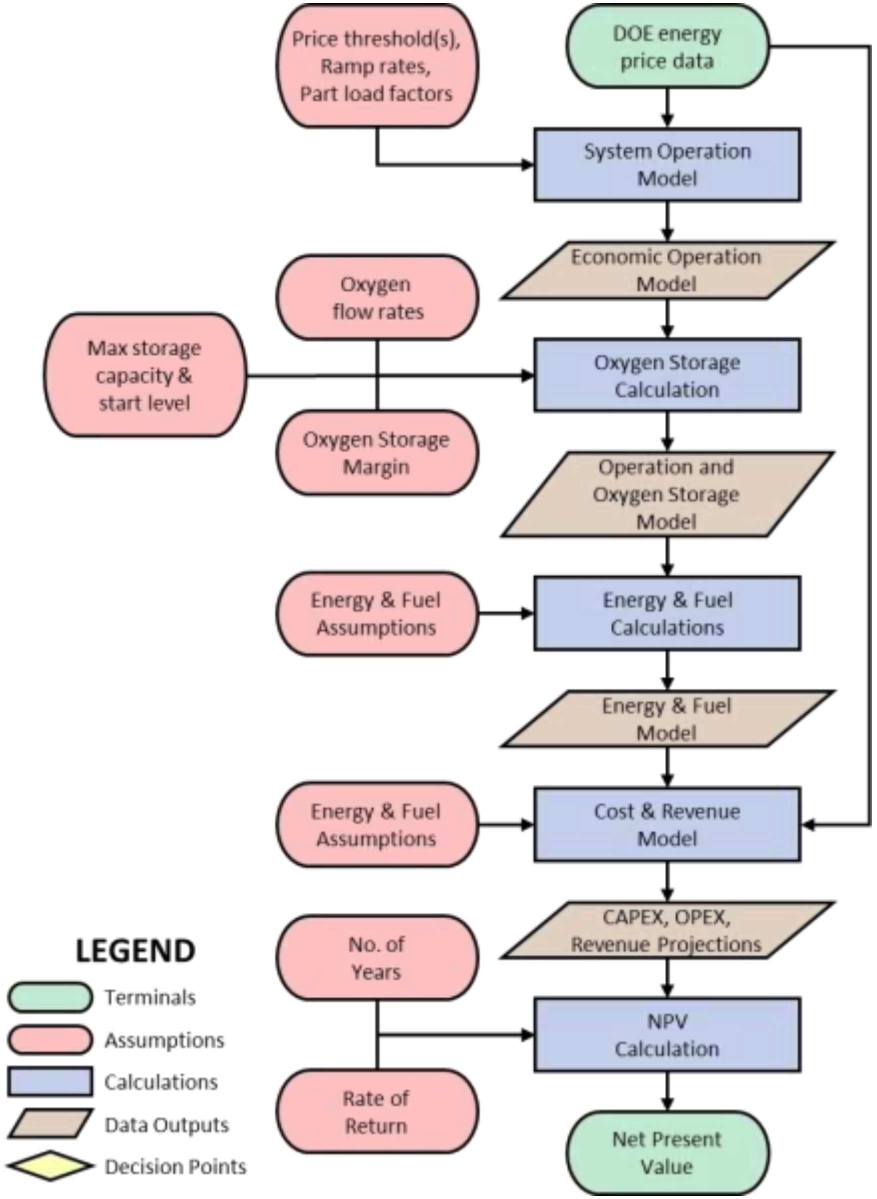



- SoftInWay developed turbomachinery aerodynamics models for the main air compressor (MAC)
- Evaluating axial, centrifugal, and combinations for the MAX
- Compressor performance (efficiency, pressure ratio, power, etc.) are evaluated at both design and off-design conditions
- One design option is shown below
  - Two axial sections with intercooling followed by 3 centrifugal stages



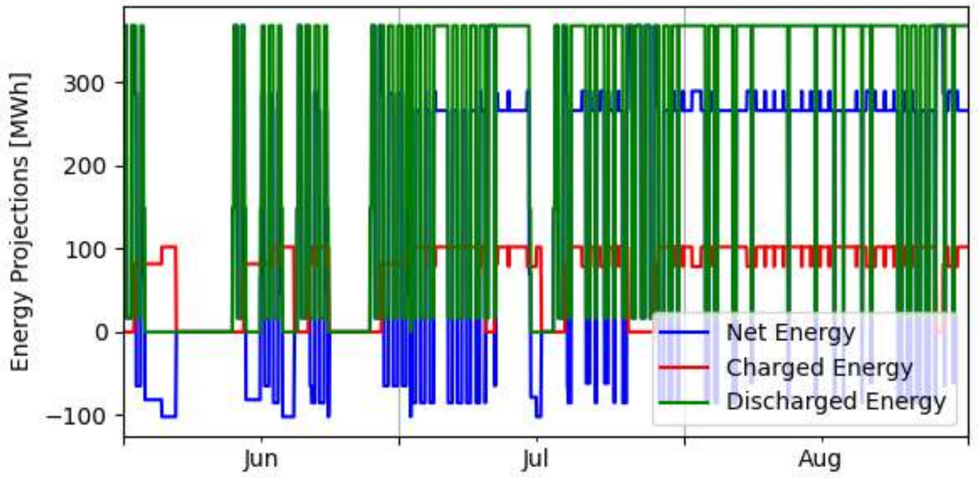
# Design and Optimization Methodology

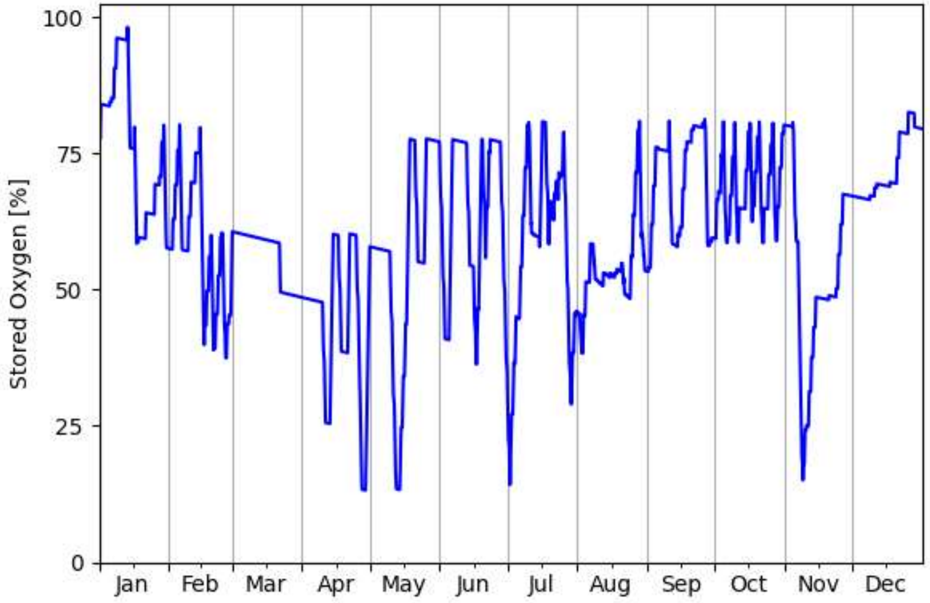
- The price scenarios are separated into useable segments based on energy price.
  - The charge and discharge systems are segmented individually
- The hourly oxygen storage level is then calculated using the segmented data
  - Code is able to shut-off or turn on the ASU or power block as needed
- NPV is optimized using a genetic algorithm with up to 8 different independent parameters
  - *Each price scenario is handled separately*
  - *Only energy considered as source of revenue*

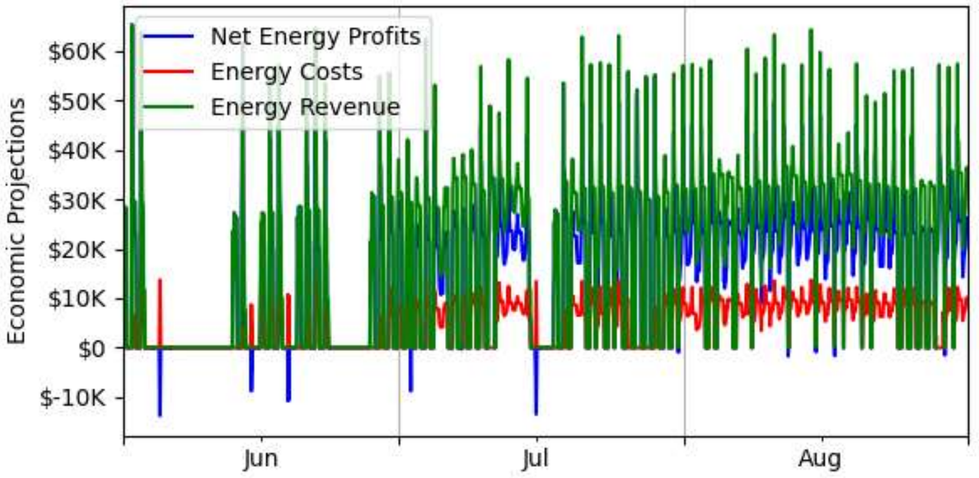


# Results from California with $100 Carbon Tax

- *Est. NPV - $636.5MM*
- *Storage Capacity – 15996 tonnes (4.2 days)*
- *Net Energy per year: 1281.5 GWh/year*
  - *Discharged: 1881.5 GWh /year*
  - *Charged: 600.0 GWh /year*

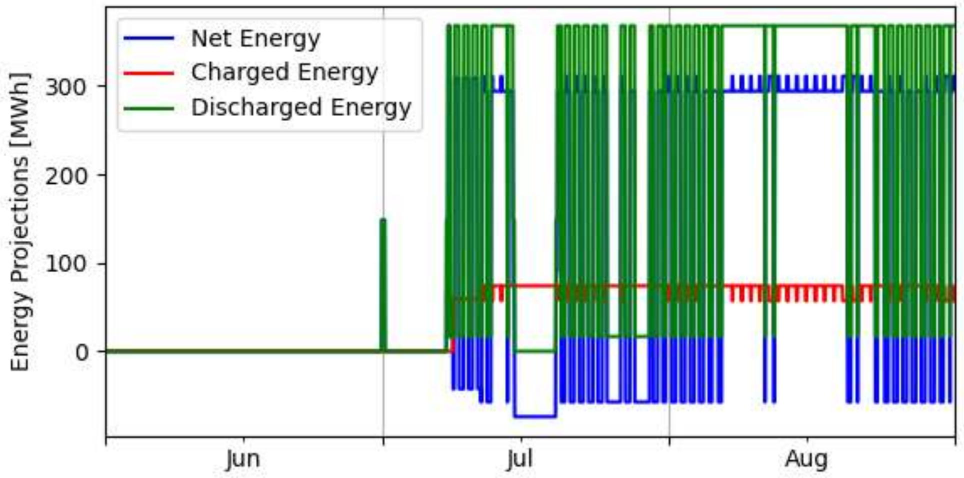


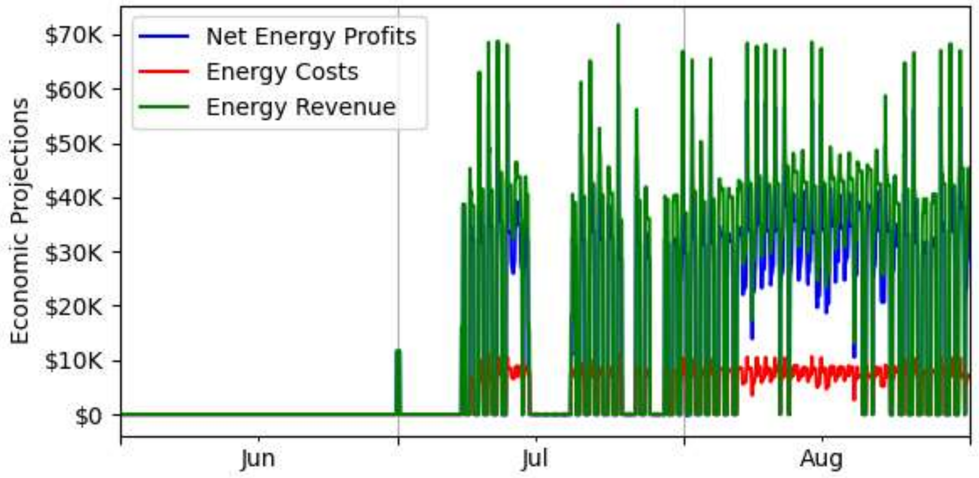



# Results from California with $150 Carbon Tax

- *Est. NPV - $568.9MM*
- *Storage Capacity – 59989 tonnes (16 days)*
- *Net Energy per year: 882.0 GWh*
  - *Discharged: 1276.1 GWh*
  - *Charged: 394.1 GWh*

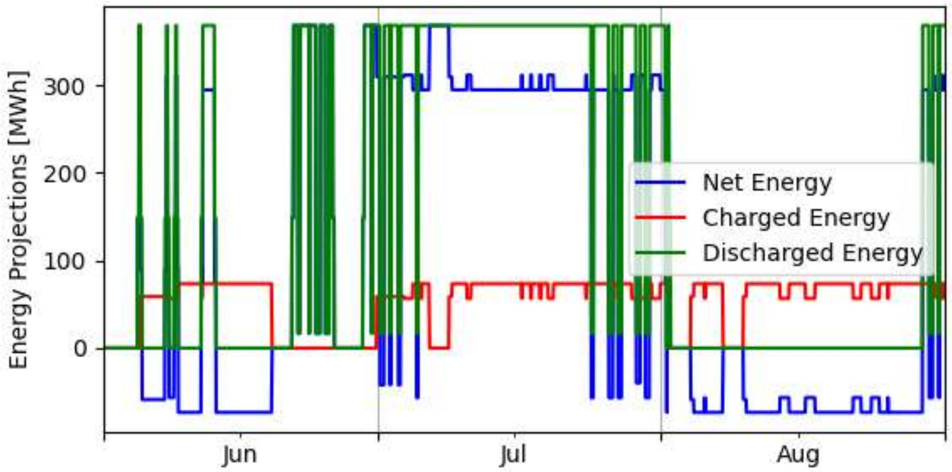


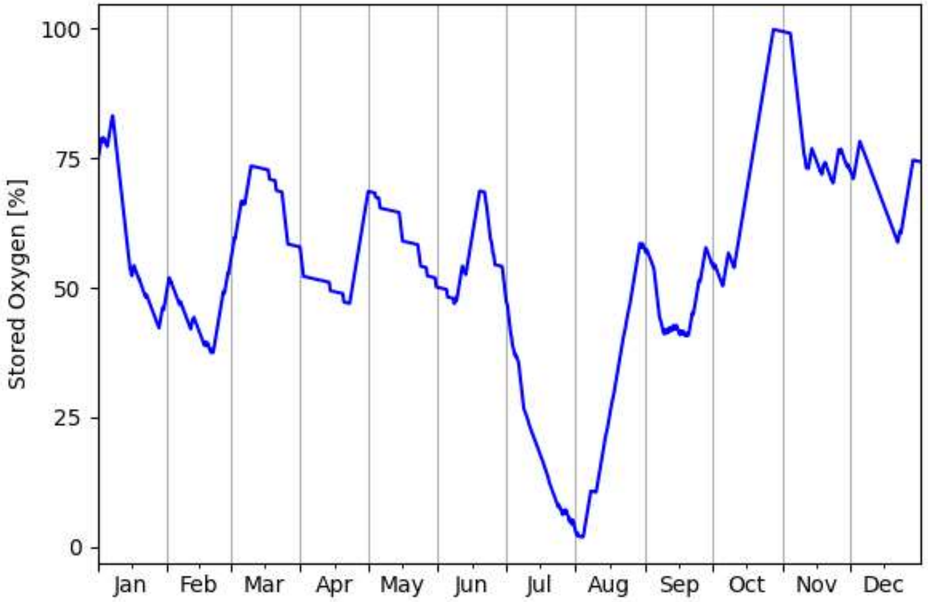


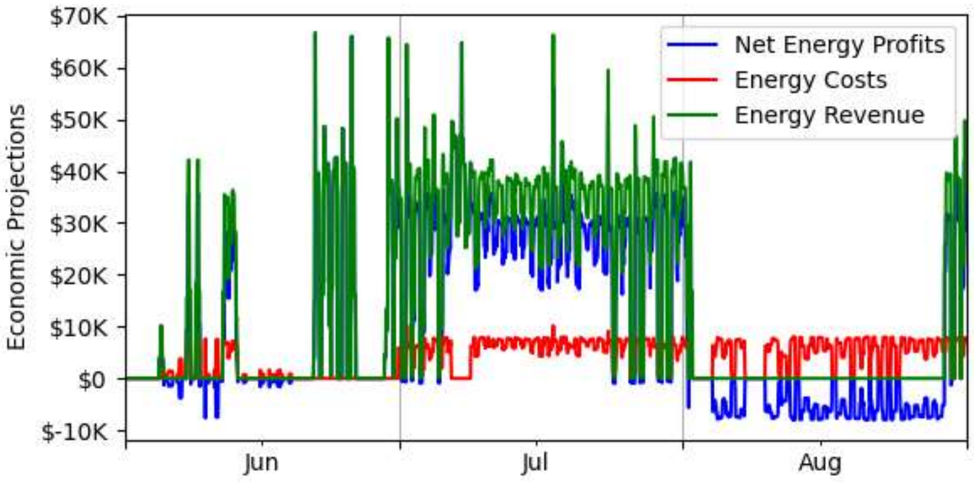


# Results from Western Pennsylvania with $150 Carbon Tax

- *Est. NPV - $415.4MM*
- *Storage Capacity – 100900 tonnes (26 days)*
- *Net Energy per year: 896.6 GWh*
  - *Discharged: 1322.5 GWh*
  - *Charged: 425.9 GWh*

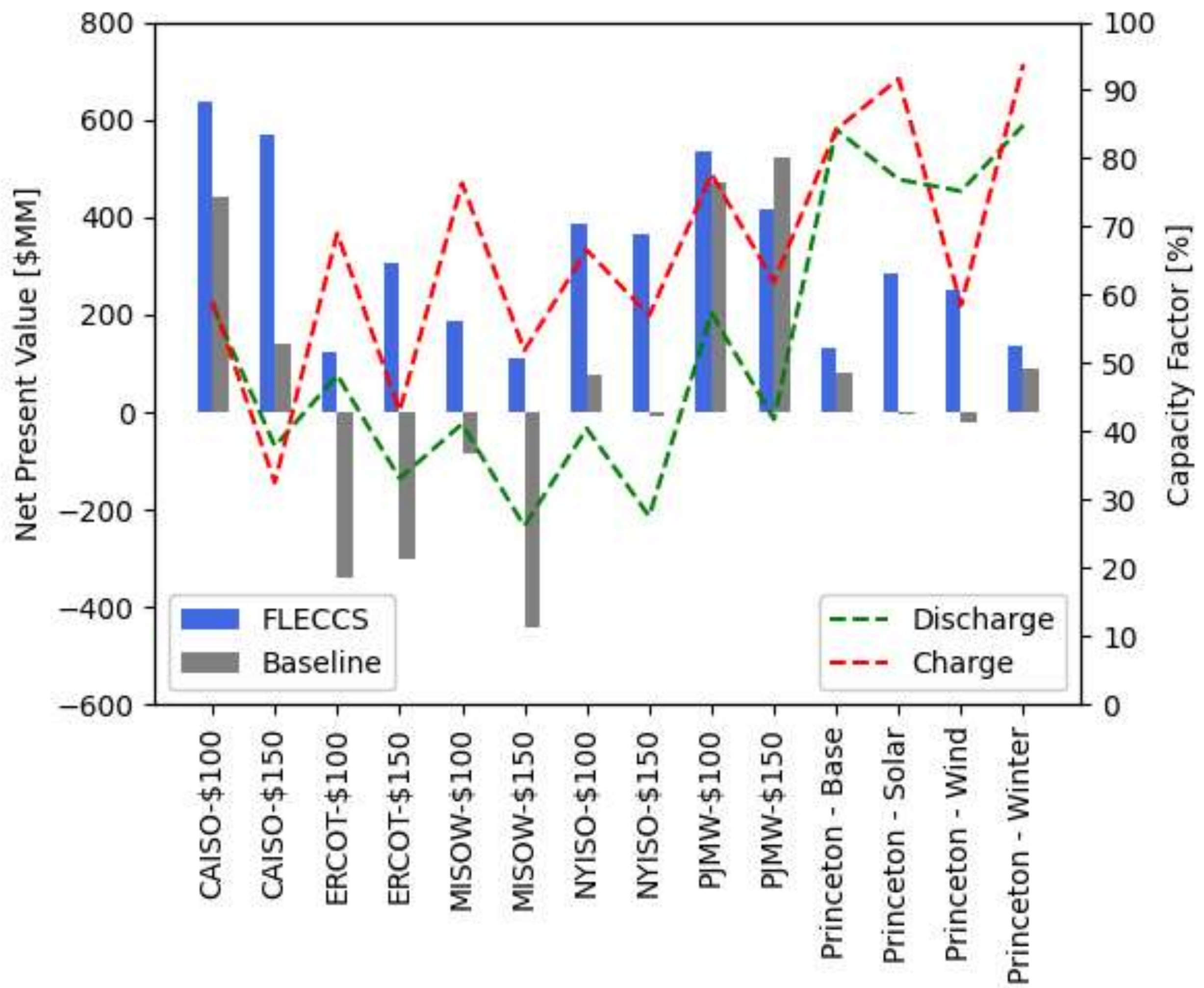


# Comparison of System Designs

- The NPV of the variable renewable energy system was positive for all cases studied
- NPV of variable renewable energy dominated grid of the future compared to baseload (92.5% capacity) assumptions for power block
- Capacity factors for the power block ranged between 25-85%
- Capacity factors for the ASU ranged between 30-95%



# Summary

- LOX production and storage provides attractive economics on variable grid pricing when coupled to the Allam-Fetvedt oxy-fuel power cycle, which provides 98% carbon capture burning either natural gas or synthesis gas from coal.
- The added capital over a baseload plant consists mostly of a large or multiple storage tanks and adding liquefaction to the ASU
- While the cost per kilogram of LOX production is almost twice of GOX, producing at times of low power spot price makes the economics attractive
- The NPV of a plant with LOX storage is better in most regions than a standard plant operating at baseload (92.5%) and contributes to levelizing the grid

# Questions?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**Stefan Cich**

**Steve White**

**Owen Pryor, Ph.D.**

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