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

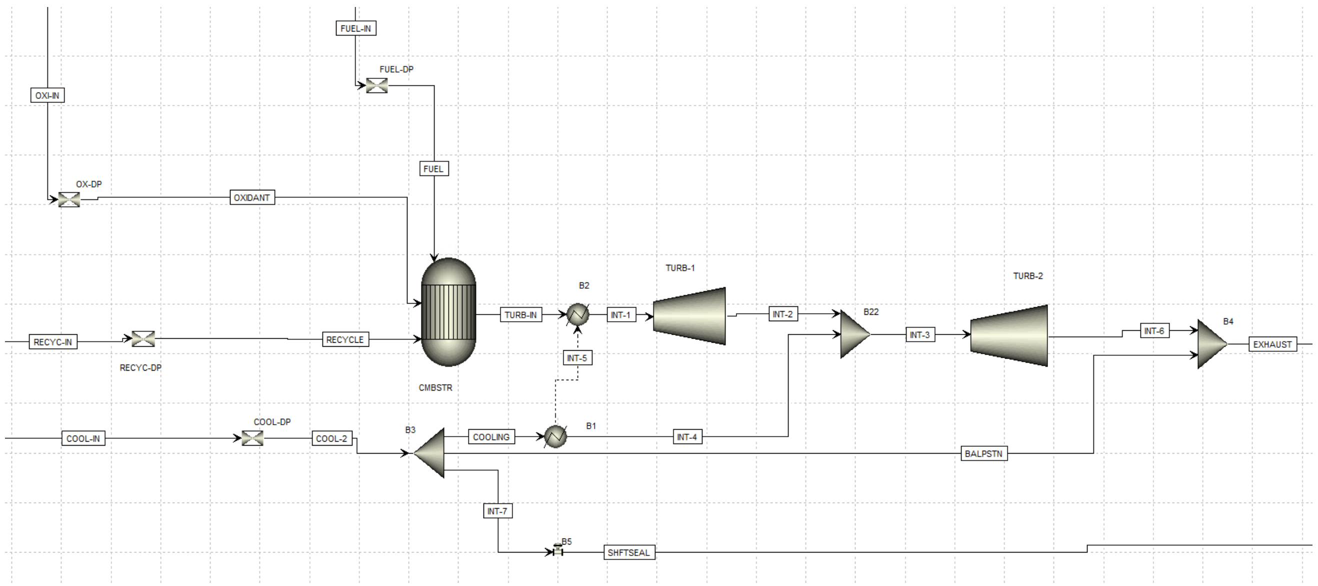
University Turbine Systems Research - Project Review Meeting

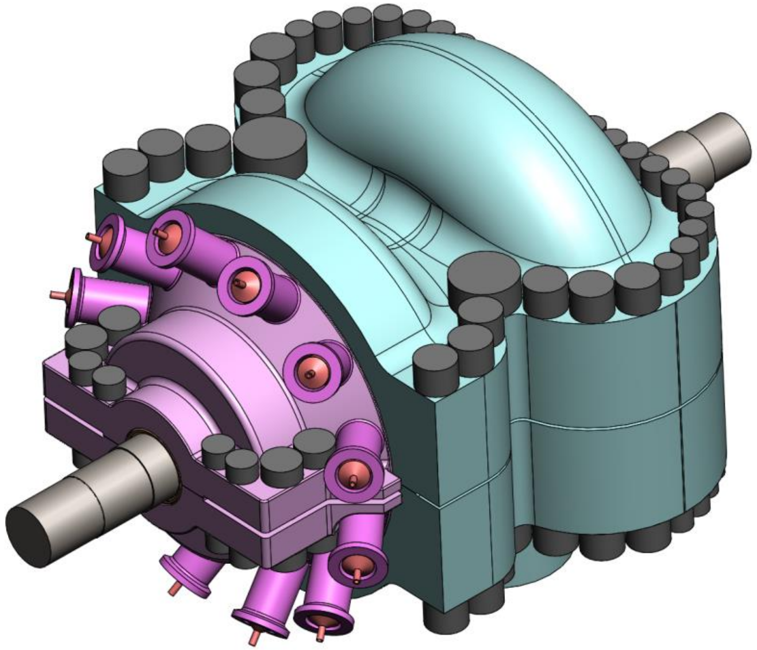
DE-FE0031929

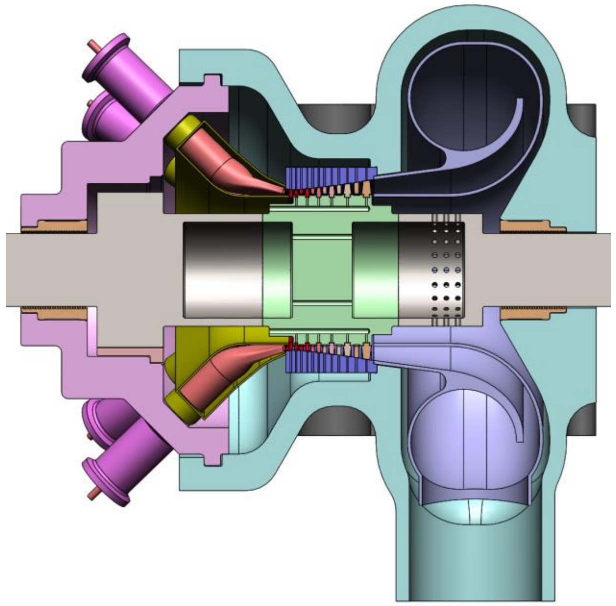
November 9, 2021

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







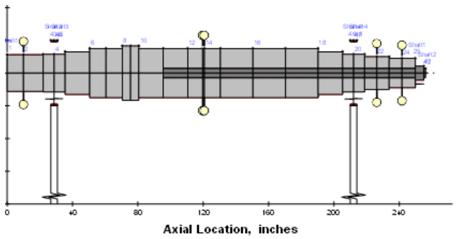
Program Overview

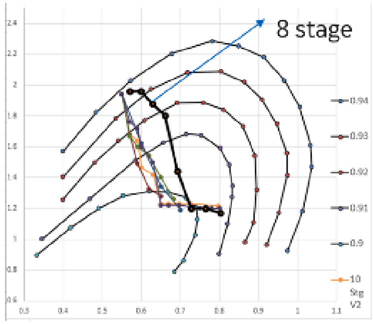
- Project Total: $6,417,610
- Budget Period 1 Total: $2,026,851
- Budget Period 2 Total: $2,562,422
- Budget Period 3 Total: $1,828,337

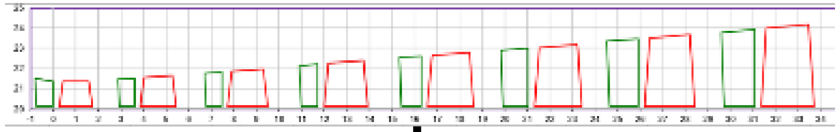
		Budget Period 1												Budget Period 2												Budget Period 3											
Task #	Description	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1.2	Initial Syngas Combustion Cycle																																				
1.2.1	Add Gasifier and Syngas Cleanup																																				
1.2.2	Scale Turbine to Desired Power Plant Size																																				
1.3	Heat Transfer Validation																																				
1.3.1	High Reynolds Number sCO2 Rig Design																																				
1.3.2	Rig Adaption for sCO2																																				
1.3.3	Impingement and Pin-Fin Assessment																																				
1.4	Turbine Conceptual Design																																				
1.4.1	Turbine Meanline Layout																																				
1.4.2	3D Modeling and Analysis of 1st Stage																																				
1.4.3	Optimize Stator-Rim Platform Cavity																																				
1.4.4	Conceptual Seal Design																																				
1.4.5	Conceptual Case and Rotor Layout																																				
1.5	Combustor Conceptual Design																																				
1.6	Material Testing																																				
1.6.1	Material Selection																																				
1.6.2	Material Test Setup Design																																				
2.1	Heat Transfer Testing																																				
2.1.1	High Re # sCO2 Rig Manufacturing																																				
2.1.2	High Re # sCO2 Testing																																				
2.1.3	Impingement Testing with sCO2																																				
2.1.4	Heat Transfer Test Blade Design																																				
2.2	Turbine Preliminary Design																																				
2.2.1	Optimized Turbine Tip																																				
2.2.2	Updated Blade Design																																				
2.2.3	Scaled Test Blade Design																																				
2.2.4	Scale Down Blade Procurement																																				
2.2.5	Preliminary Case and Rotor Layout																																				
2.3	Material Testing - Autoclave & Cyclic																																				
2.4	Updated Syngas Combustion Cycle																																				
2.5	Techno Economic Assessment																																				
3.1	Heat Transfer Testing of Turbine Blade																																				
3.1.1	Manufacturing of Test Blade Articles																																				
3.1.2	Testing of Modified Cooled Turbine Blades																																				
3.1.3	Scaled Down Condition Aerothermal Commission																																				
3.1.4	Scaled Down Condition Aerothermal Blade Test																																				
3.2	Turbine Detailed Design																																				
3.2.1	Final Stage 1 Nozzle and Blade Design																																				
3.2.2	Detailed Rotor and Case Design																																				
3.2.3	Cost Estimates																																				
3.3	Updated Thermal and Cycle Models																																				
3.4	Final Techno Economic Assessment																																				

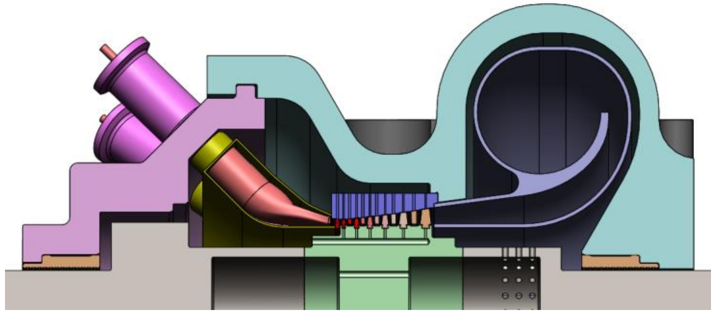
Program Overview

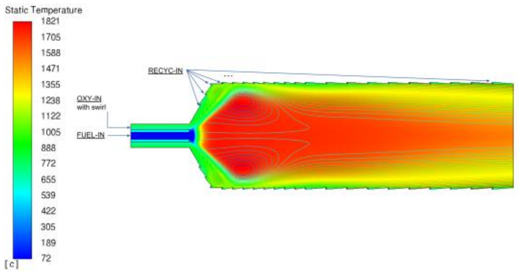
- Three Step Design Approach
  - Budget Period 1 – Conceptual Design
    - Turbine case and rotor, aerodynamic flowpath, and combustor layout with initial analysis and calculations to justify that the design can meet cycle requirements
  - Budget Period 2 – Preliminary Design
    - Updated design of all critical components (1st 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

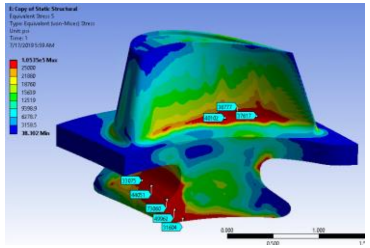




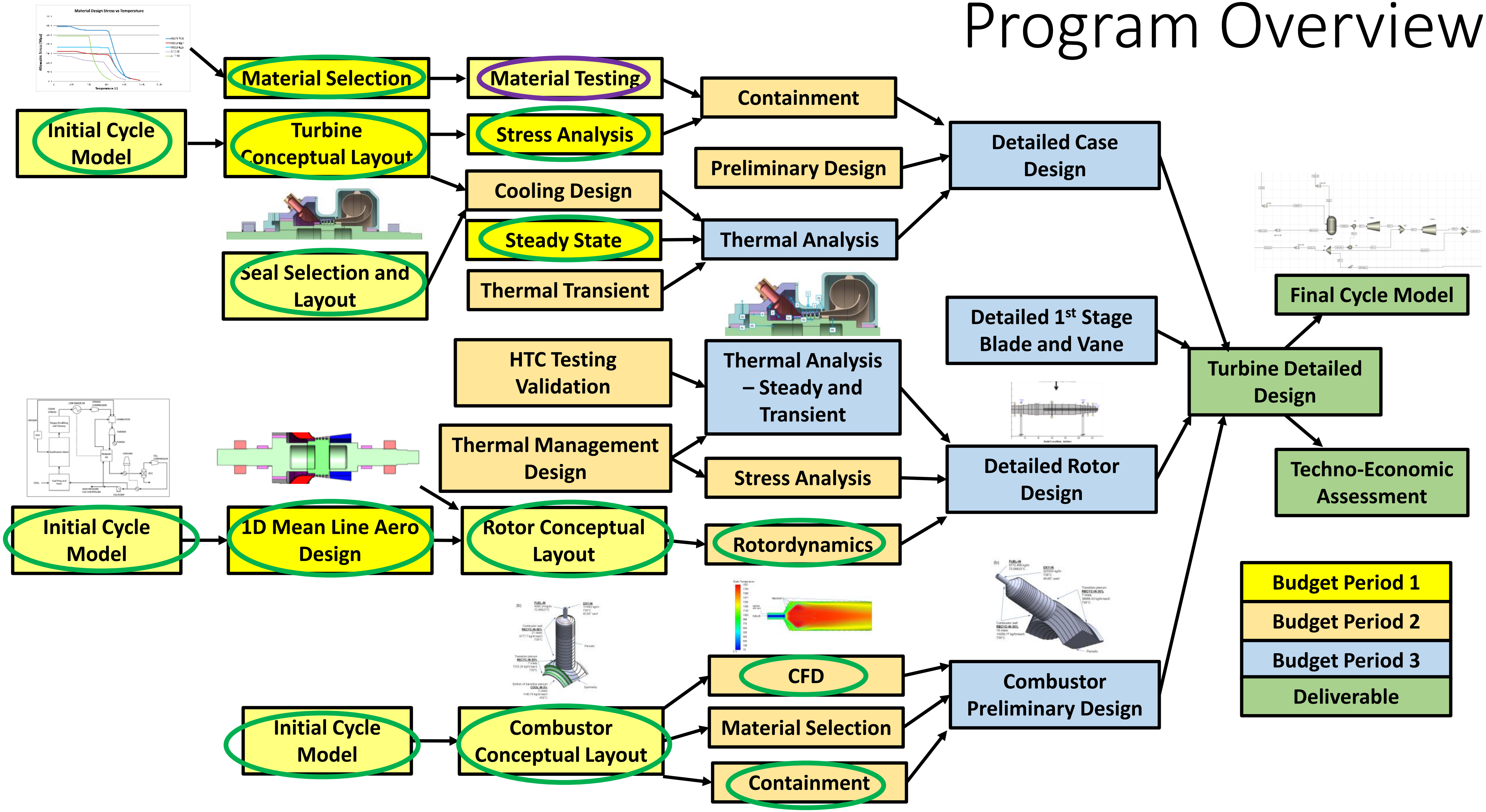




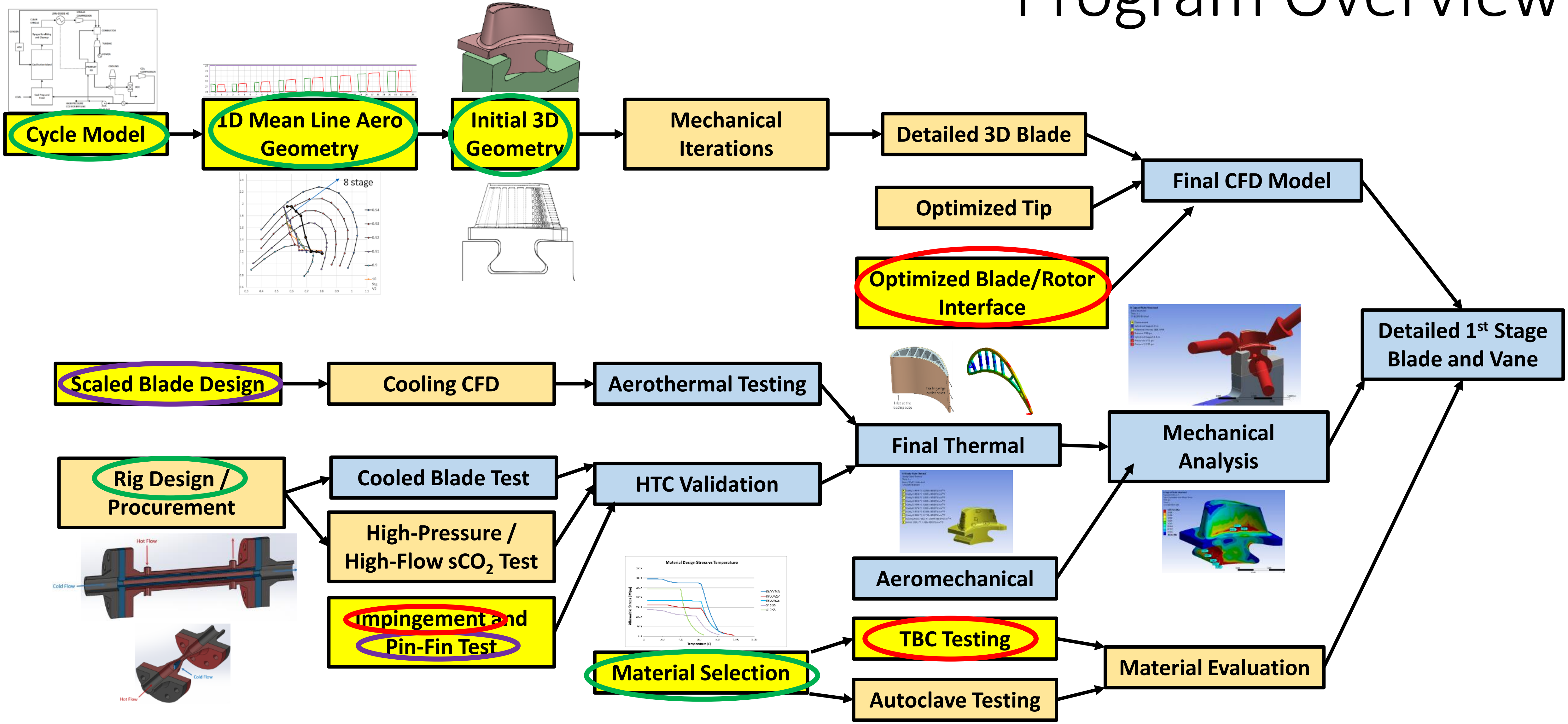




Program Overview



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

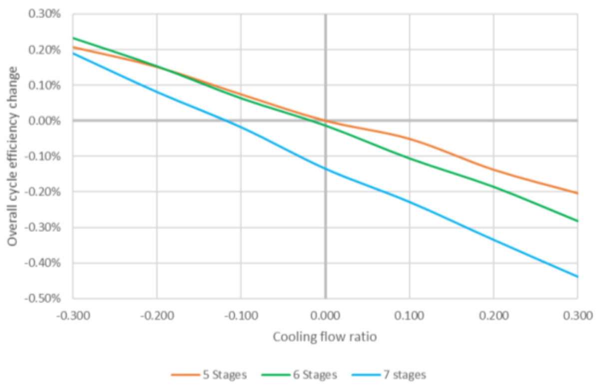
BP1 – Technical Summary

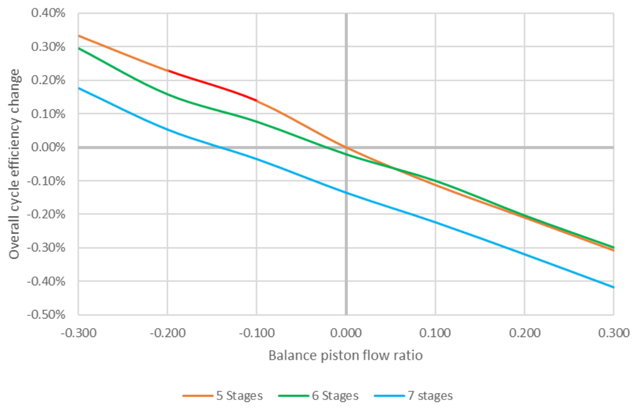
- Task 1.2 – Initial Syngas Combustion Cycle
  - Modify a 100% Natural gas Oxy-Combustion Cycle with syngas. Requires addition of Gasifier and Cleanup
  - Look at impact of various syngas (high-CO & high-H_2) fuels and evaluate performance
- Task 1.3 – Heat Transfer Validation
  - Fundamental heat transfer 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 1st 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%

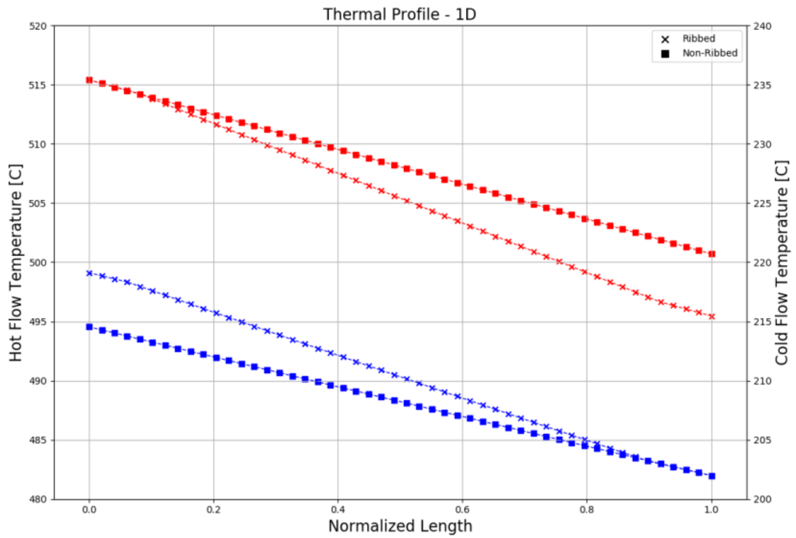


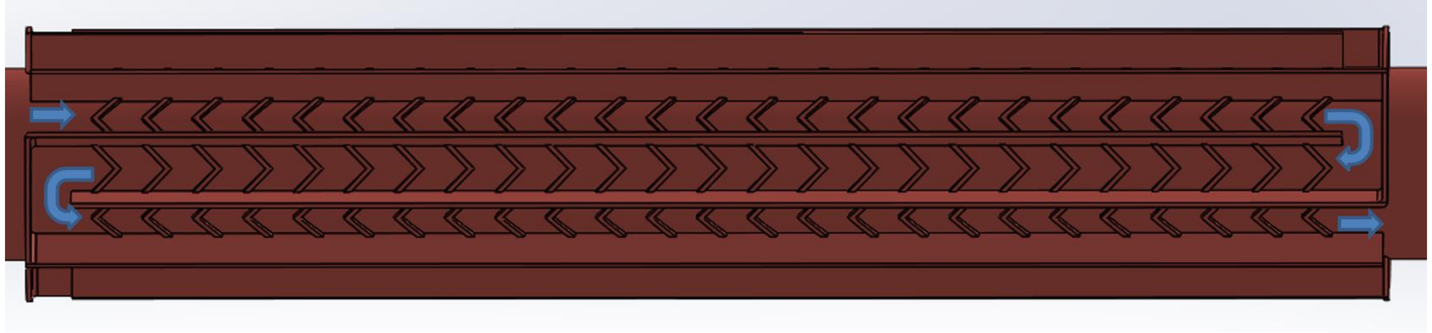


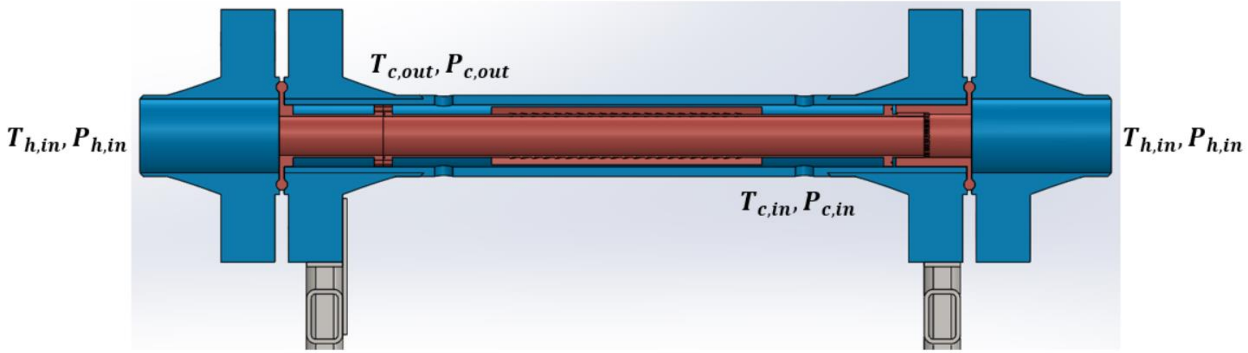
Task 1.3 – Heat Transfer Validation

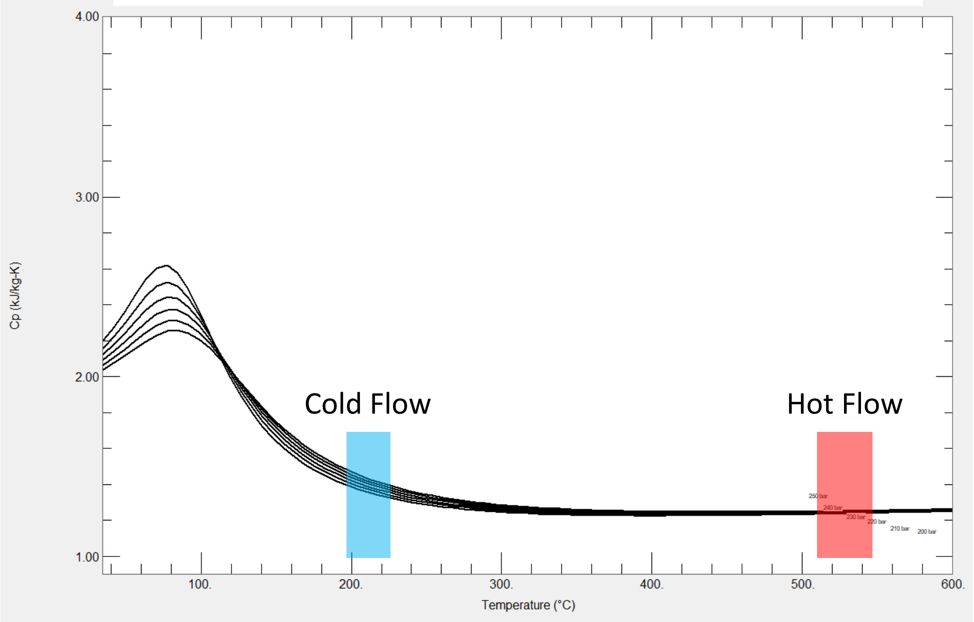
Task 1.3.1 – High Reynolds Number sCO_2 Test Rig Design

- 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 15-20ºC Temperature Rise. Looking at multi-pass option
- Important to avoid near dome temperatures with high variations in fluid properties.
- Currently looking at operating around 200ºC for the cold flow and around 525ºC for the hot flow.





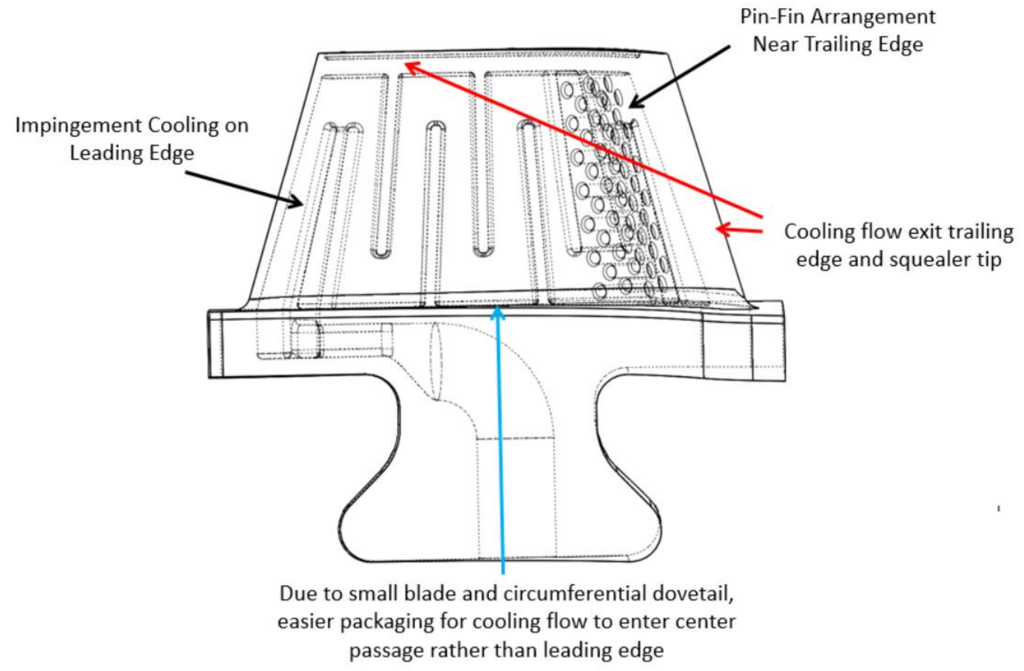


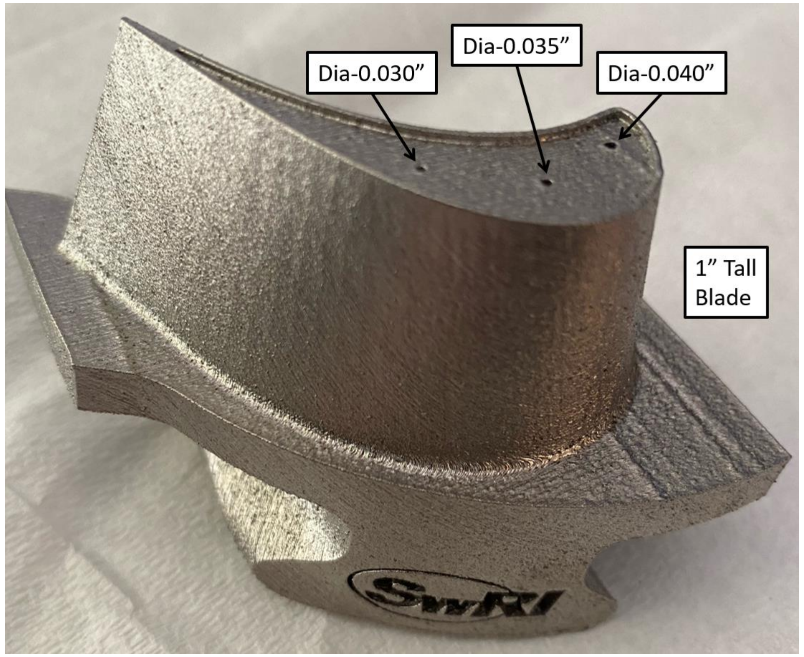


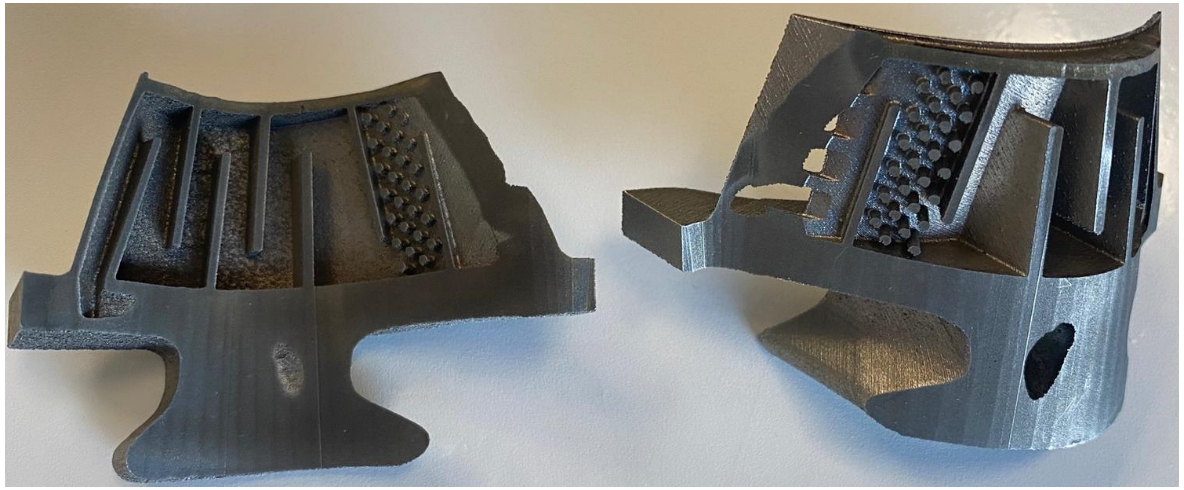
Task 1.3 – Heat Transfer Validation

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



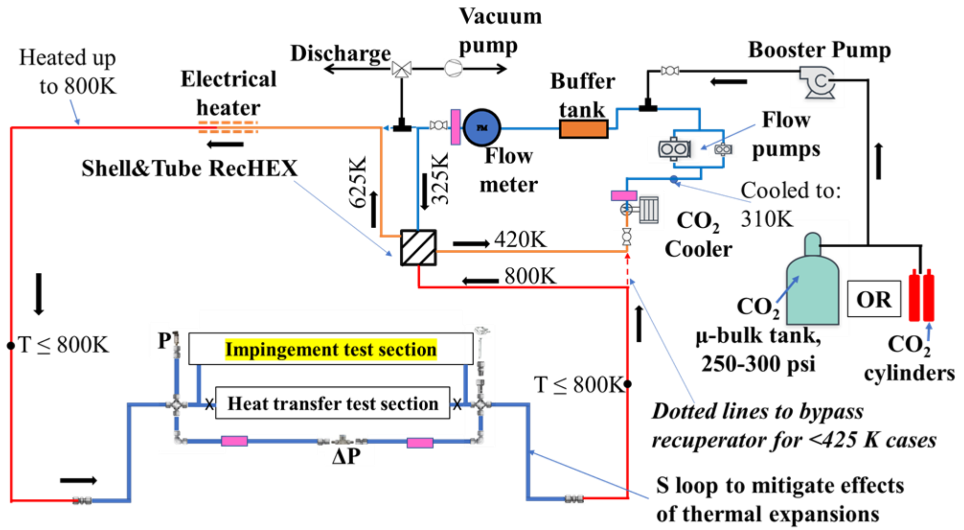




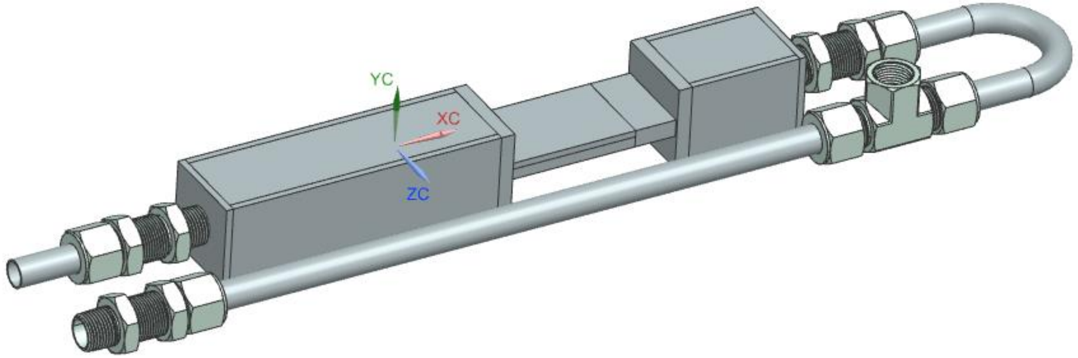
Task 1.3 – Heat Transfer Validation

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

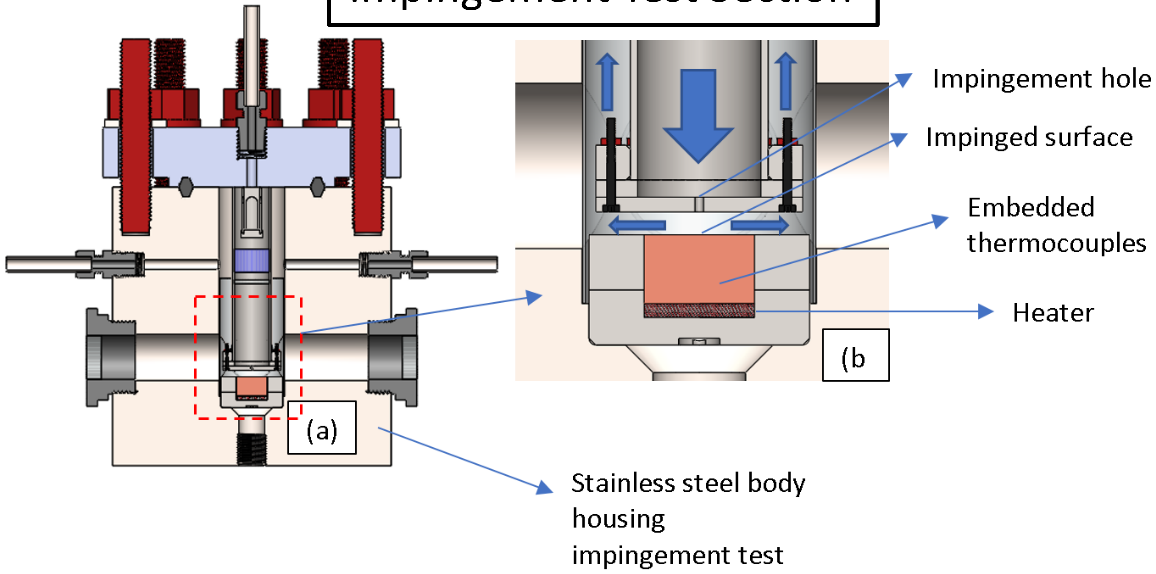
- Impingement Test Section
  - This test will involve a single jet with a heated copper plate
  - Heat transfer will be measured by measuring required energy input into the copper plate to maintain temperature
  - Current limitations allow for a single hole to be tested, but that geometry can be changed 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



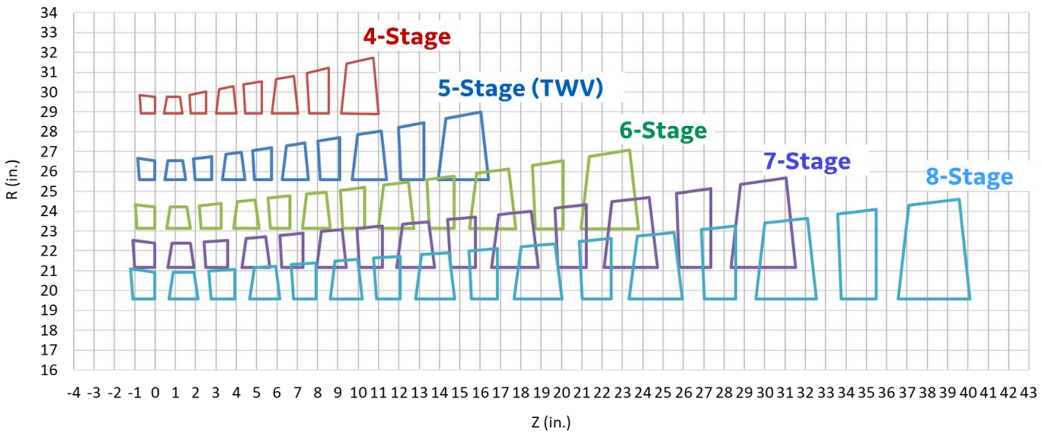
Impingement Test Section

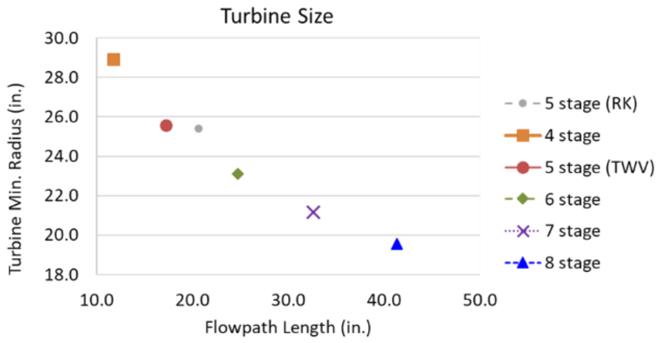


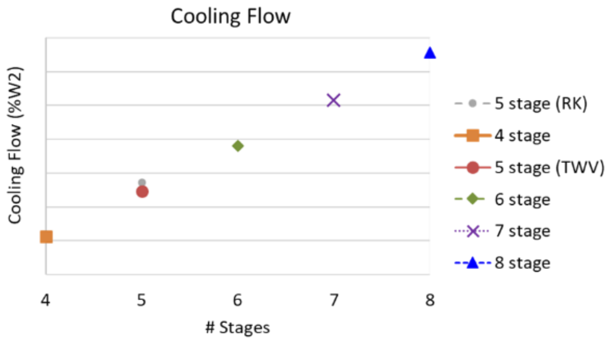
Task 1.4 – Turbine Conceptual Design

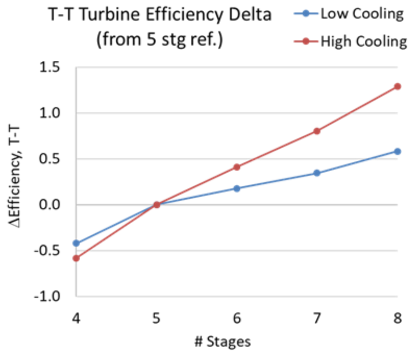
Task 1.4.1 – Turbine Meanline Layout

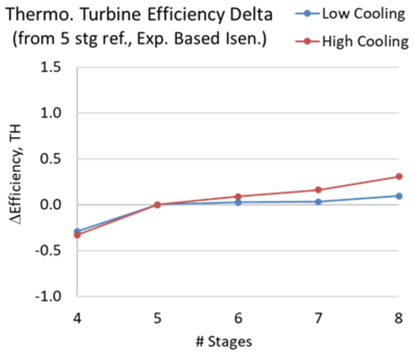
- With updated cycle modeling complete, early work was focused on updating the Turbine Meanline Layout and picking the optimal flowpath for this turbine
- Original design was a very high level layout and needed to be updated with more time and funding a long with more trade studies
  - Model Updates
    - 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
- **<u>6-Stage design chosen</u>**

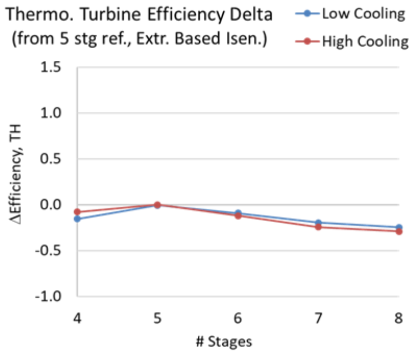




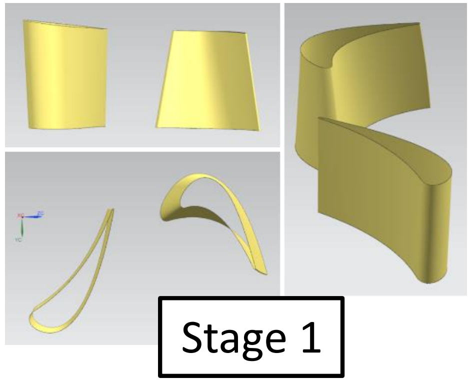


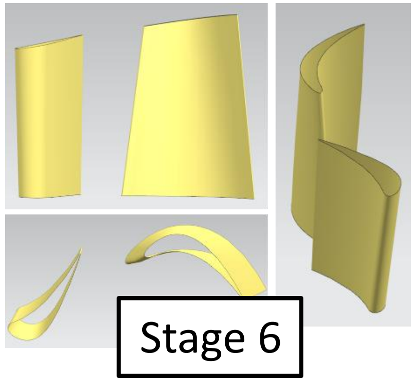






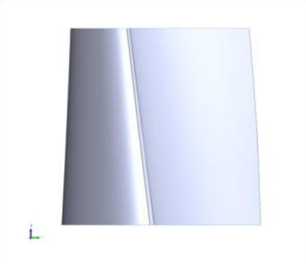
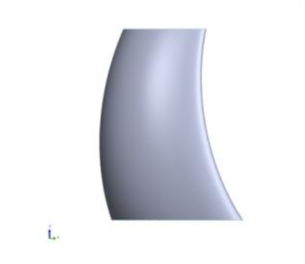
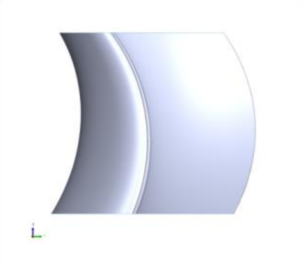
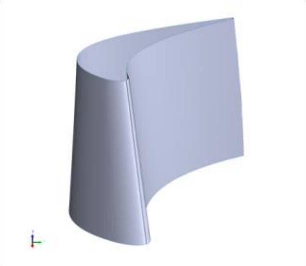
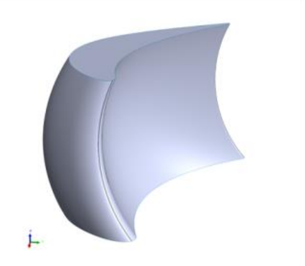
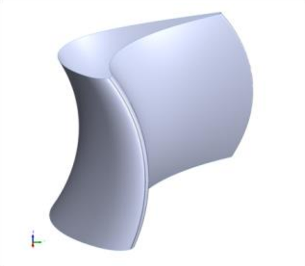
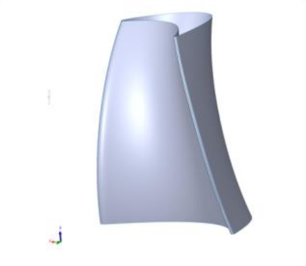
Task 1.4 – Turbine Conceptual Design

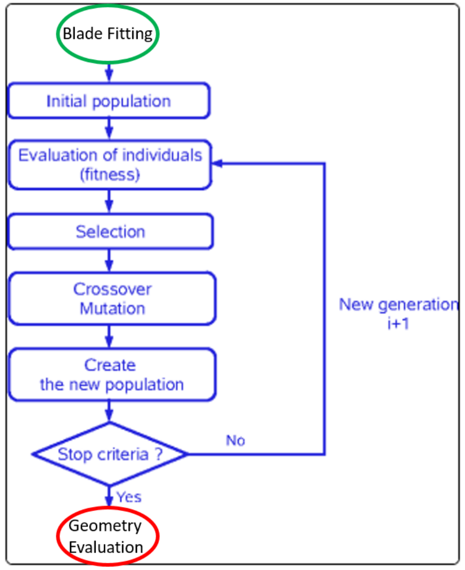


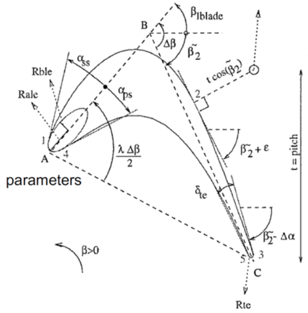


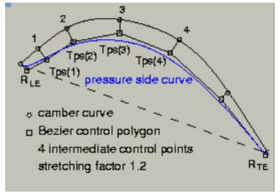
<u>Task 1.4.2 – 3D Modeling and Analysis of 1st Stage</u>

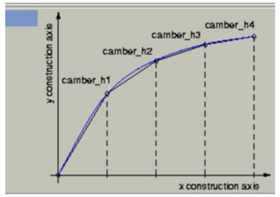
- 3D Models and Meanline produced by GE are passed to Purdue for Optimization
- Purdue is performing optimization sweeps by creating a parameterized linear model that matches the 3D smooth model closely
- Parameters of Concern:
  - Optimization focus: Sweep, stacking, lean, stagger, Camber, Span
  - 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

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





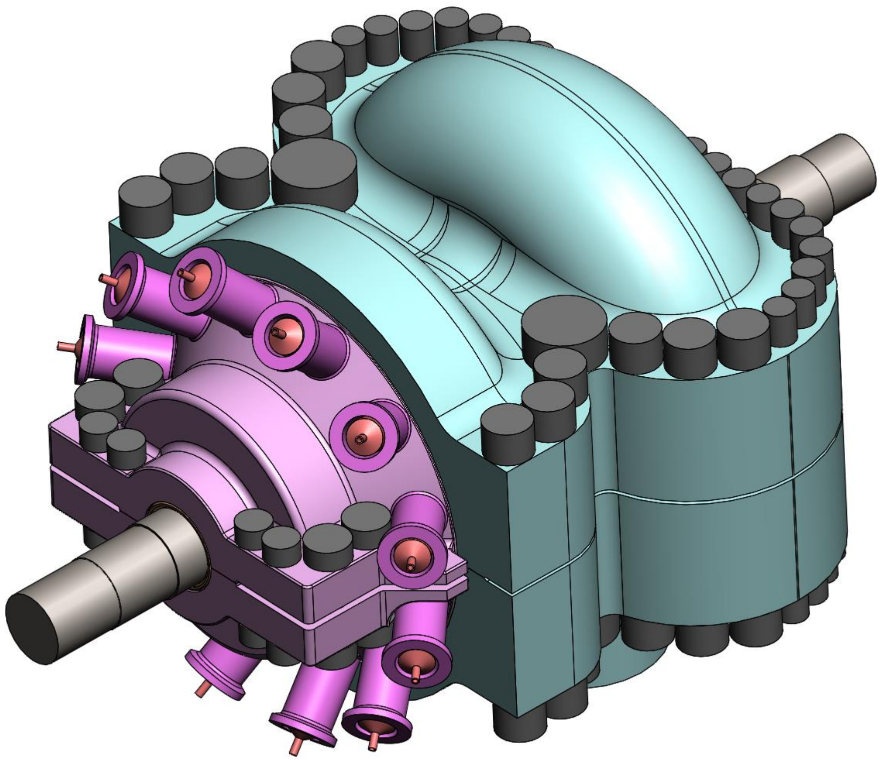


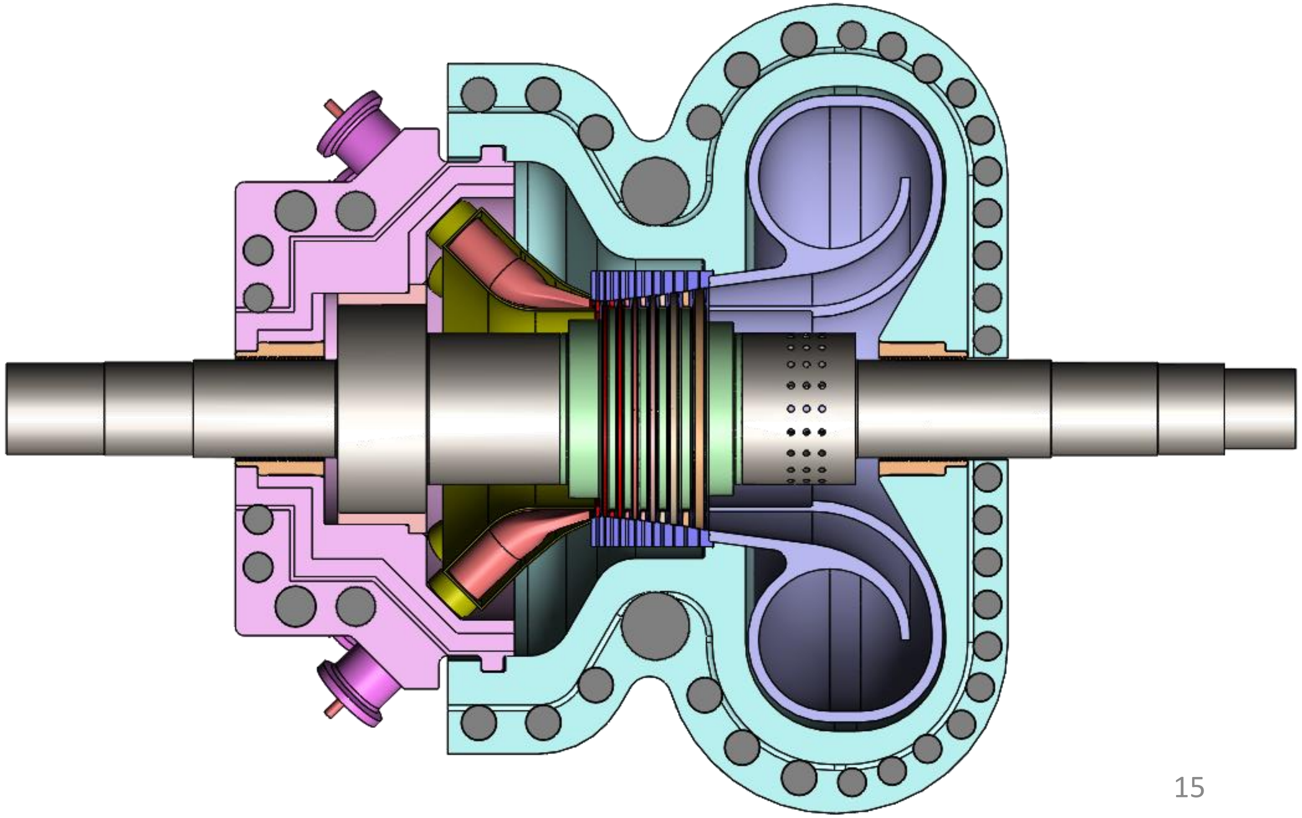


Task 1.4 – Turbine Conceptual Design

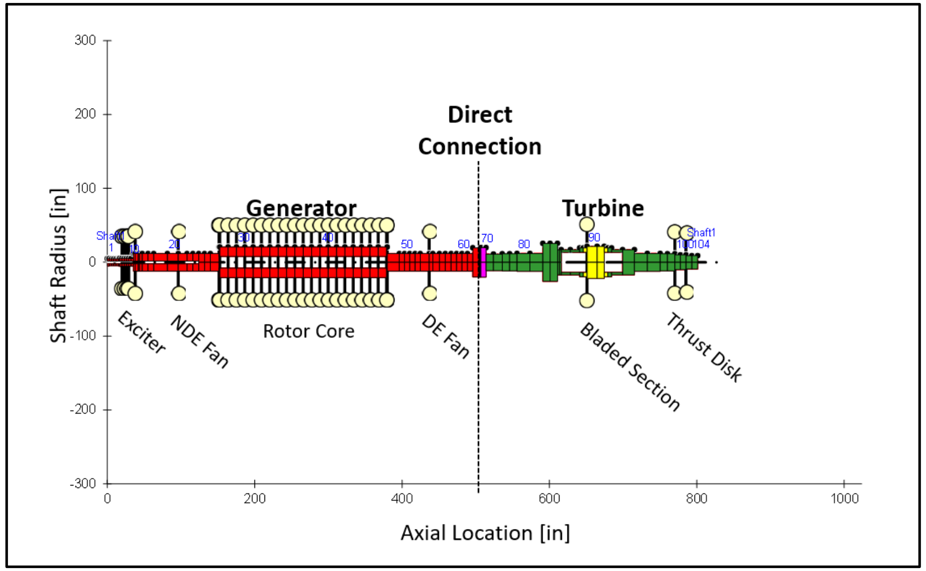
Task 1.4.5 – Conceptual Layout

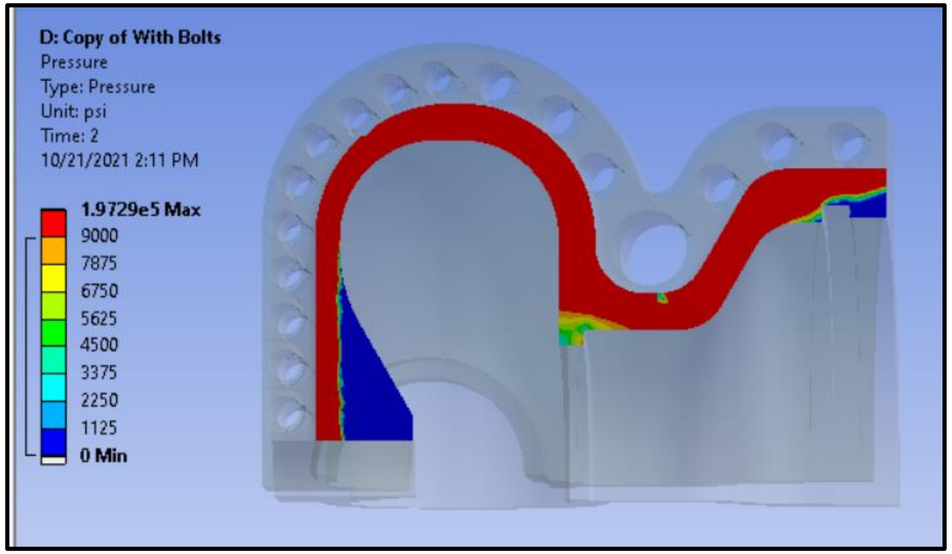
- Main focus of BP1 has been on updating the case layout with the chosen aerodynamic flowpath. The main changes to the layout at the beginning of the program
  - Evaluation of Split Case concept with supporting FEA (simplify assembly and disassembly procedure)
  - Updating of Diffuser Flowpath to reduce 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

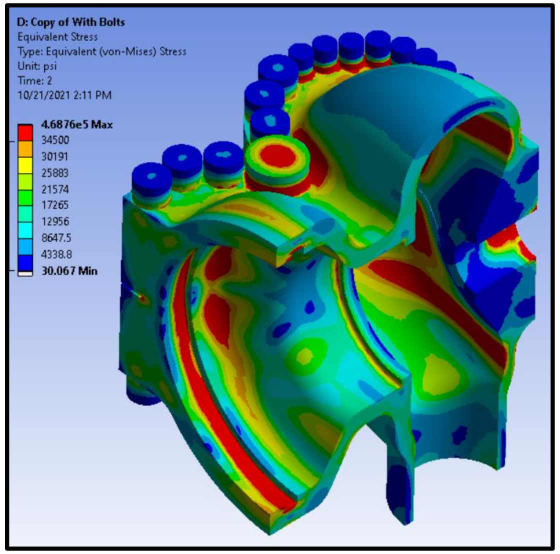


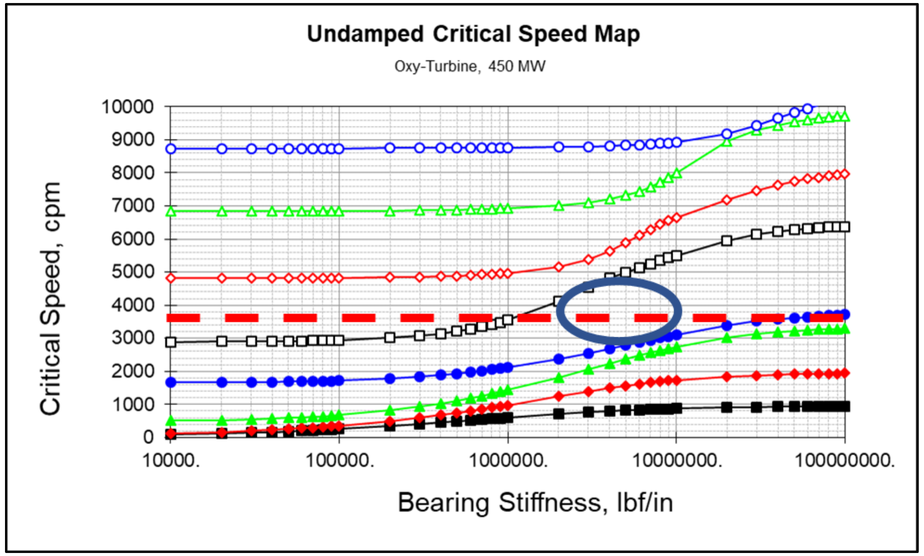


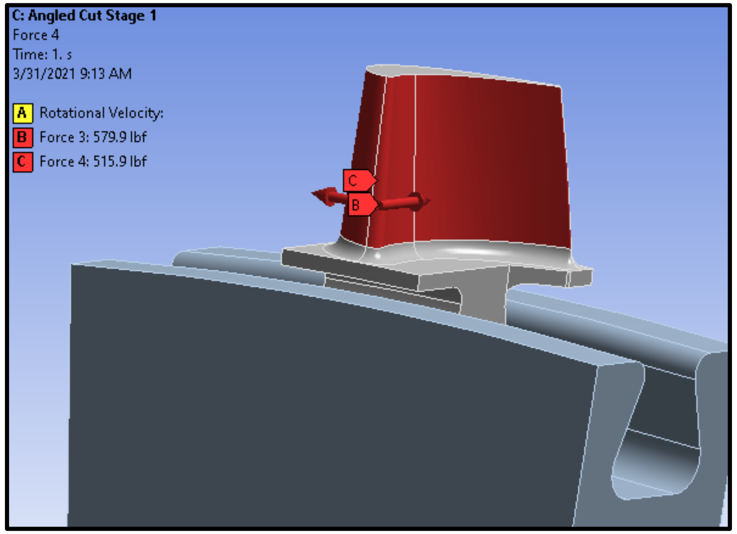
Task 1.4 – Turbine Conceptual Design

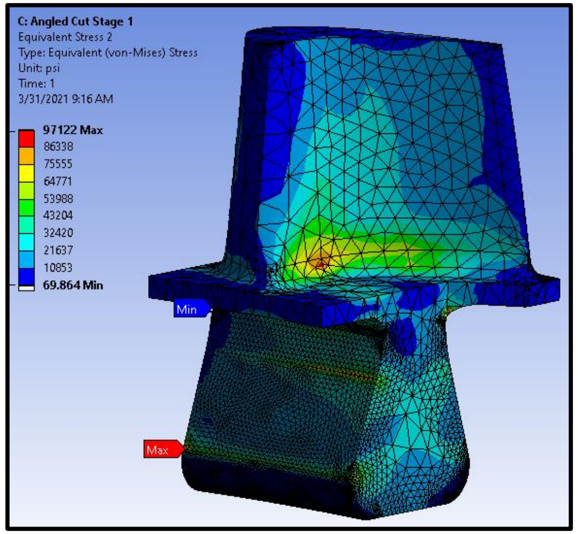






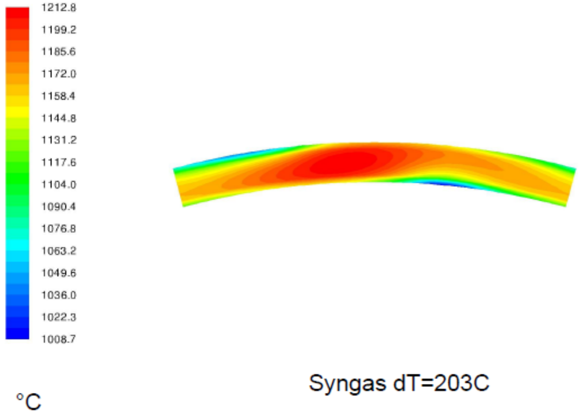


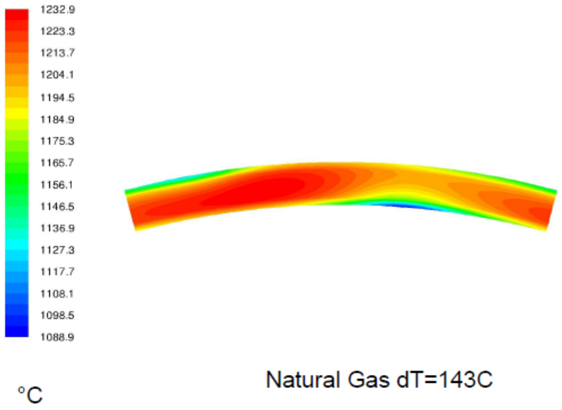




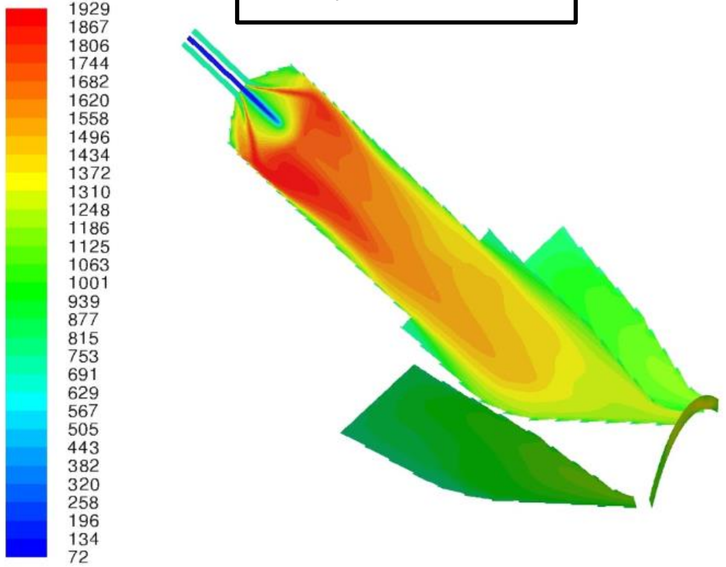
Task 1.5 – Combustor Conceptual Design

- 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 60°C higher than 100% methane (open annulus)

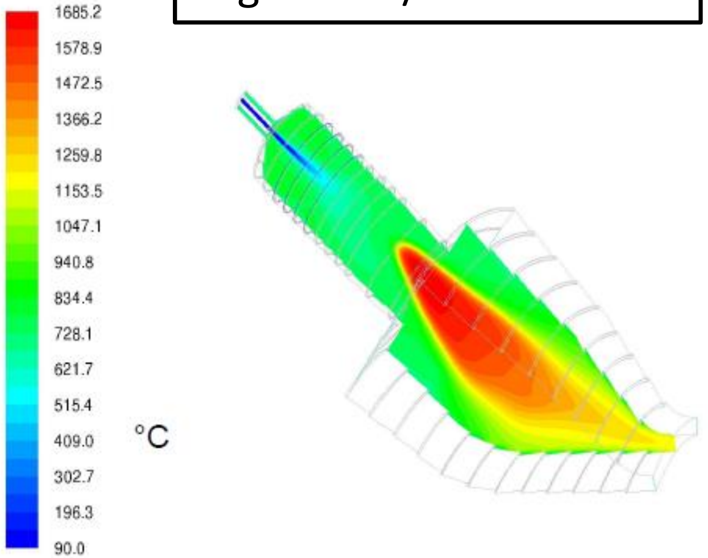




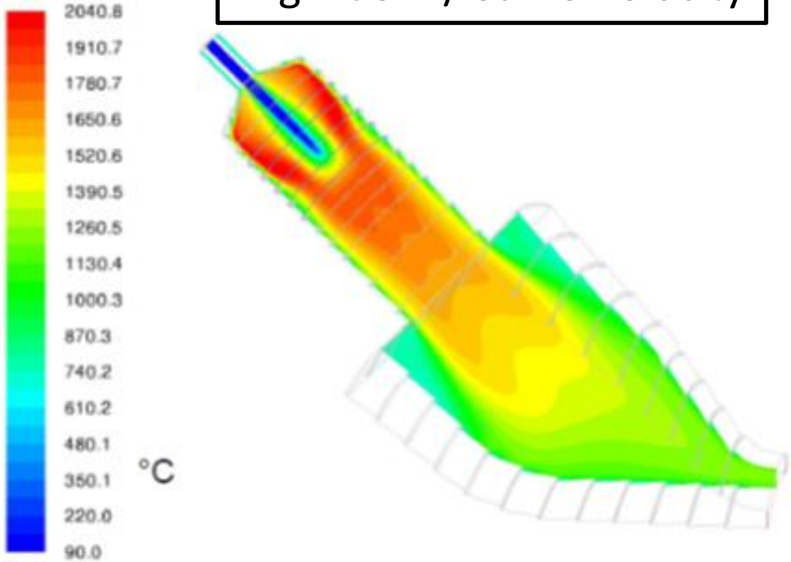
100% Methane



High-CO w/ Same Nozzle

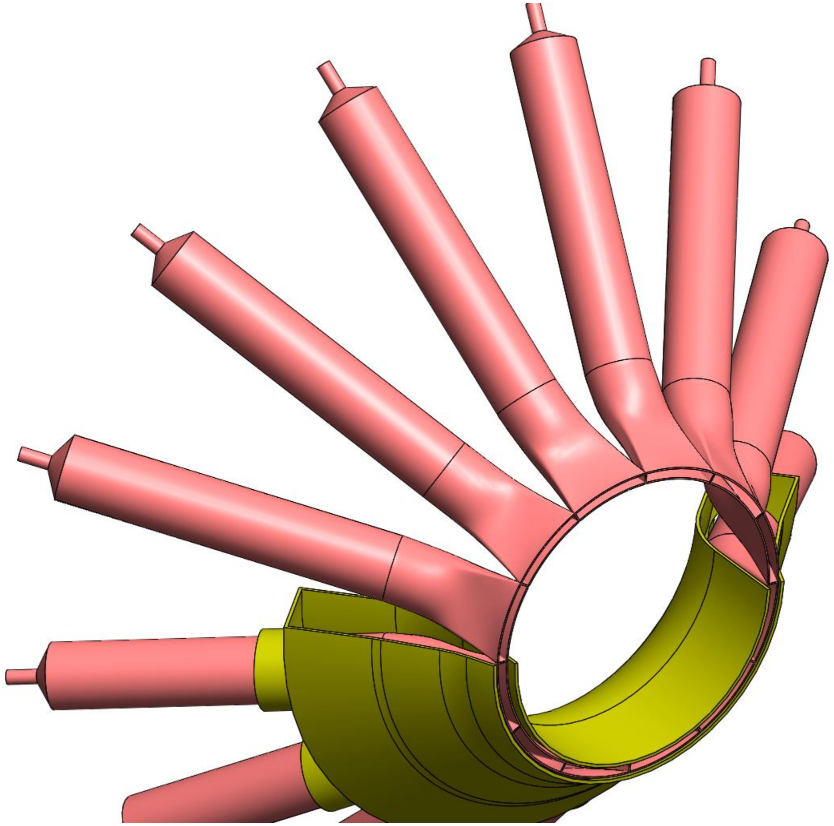


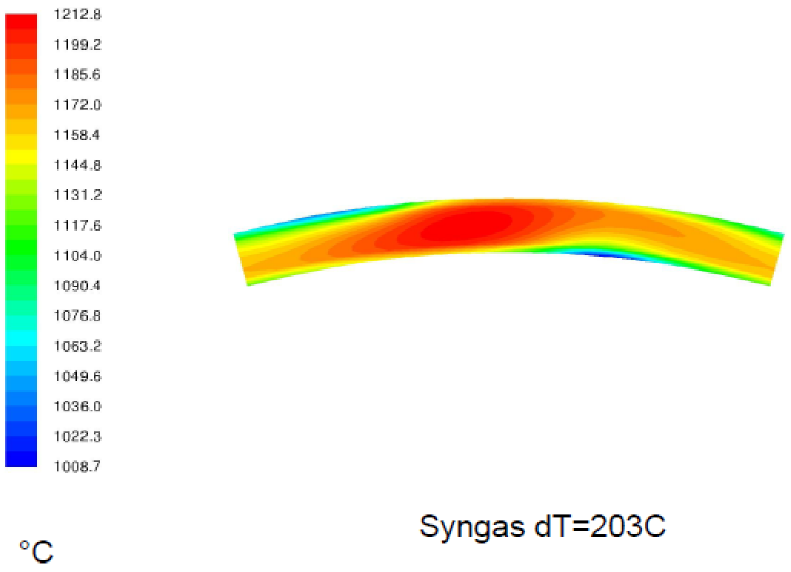
High-CO w/ Same Velocity

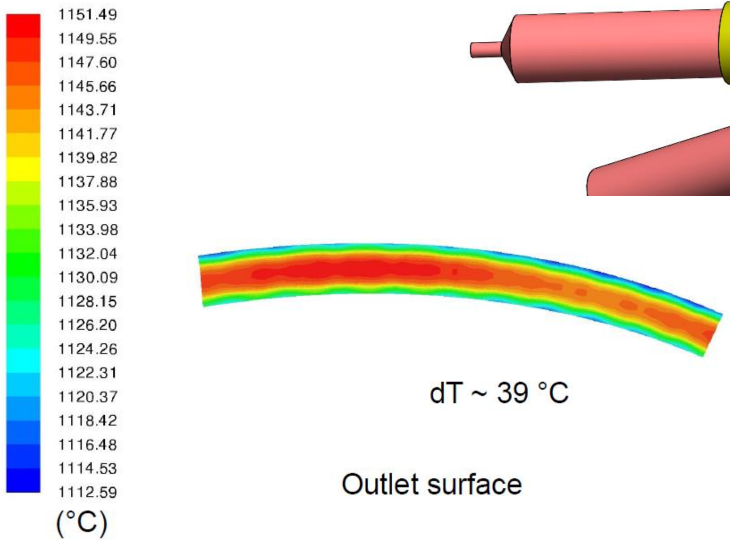


Task 1.5 – Combustor Conceptual Design

- 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





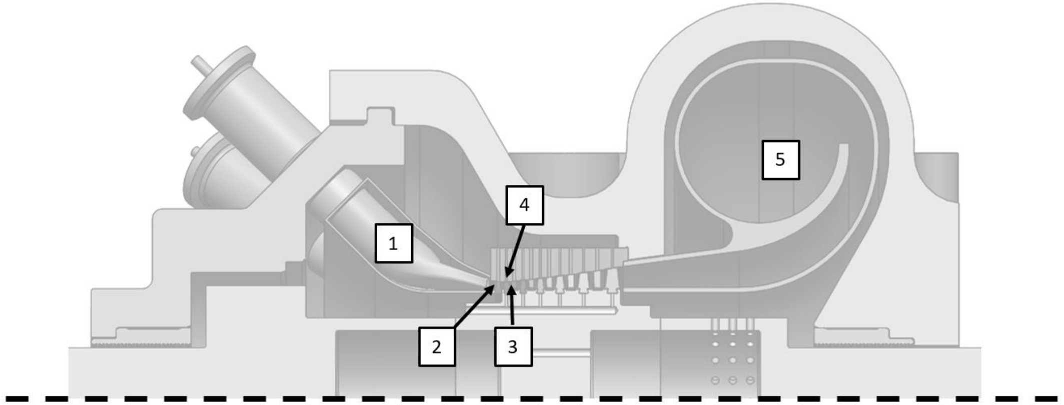


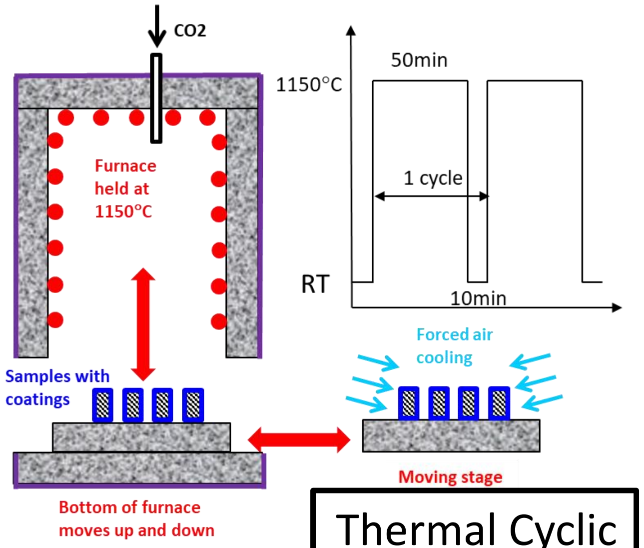
Task 1.6 – Material Testing

Task 1.6.1 – Material Selection

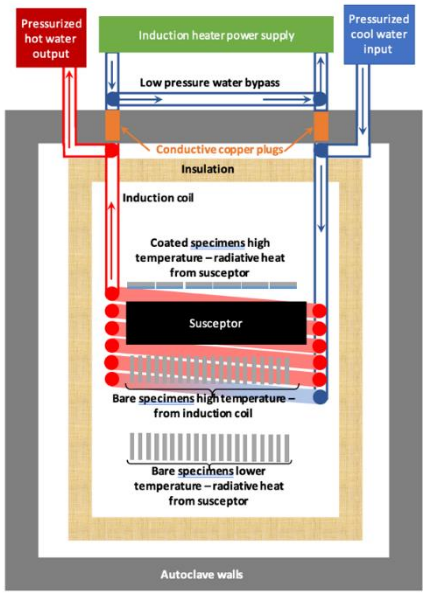
- Initial Material work was focused on establishing a baseline list of materials that could potentially be used in this turbine based on previous research and published data
- This required an initial understanding of where these materials would be used and what kind of conditions they would be seeing
- 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 21st 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 1st stage of gas turbines, there is a chance that shrouded blades could be effective for the 1st 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?