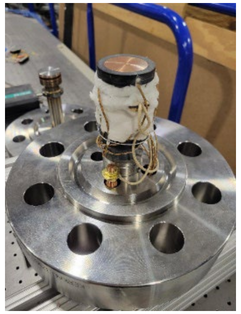
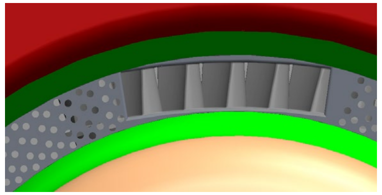
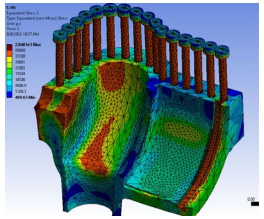
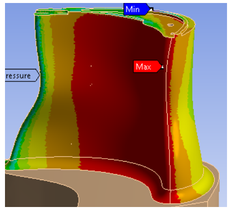
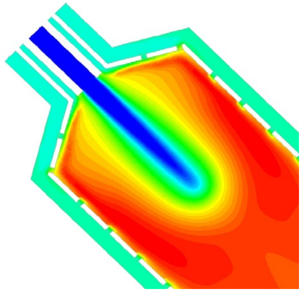




Development of Syngas Oxy-Combustion Turbine for Use in Advanced sCO_2 Power Cycles

University Turbine Systems Research - Project Review Meeting

DE-FE0031929

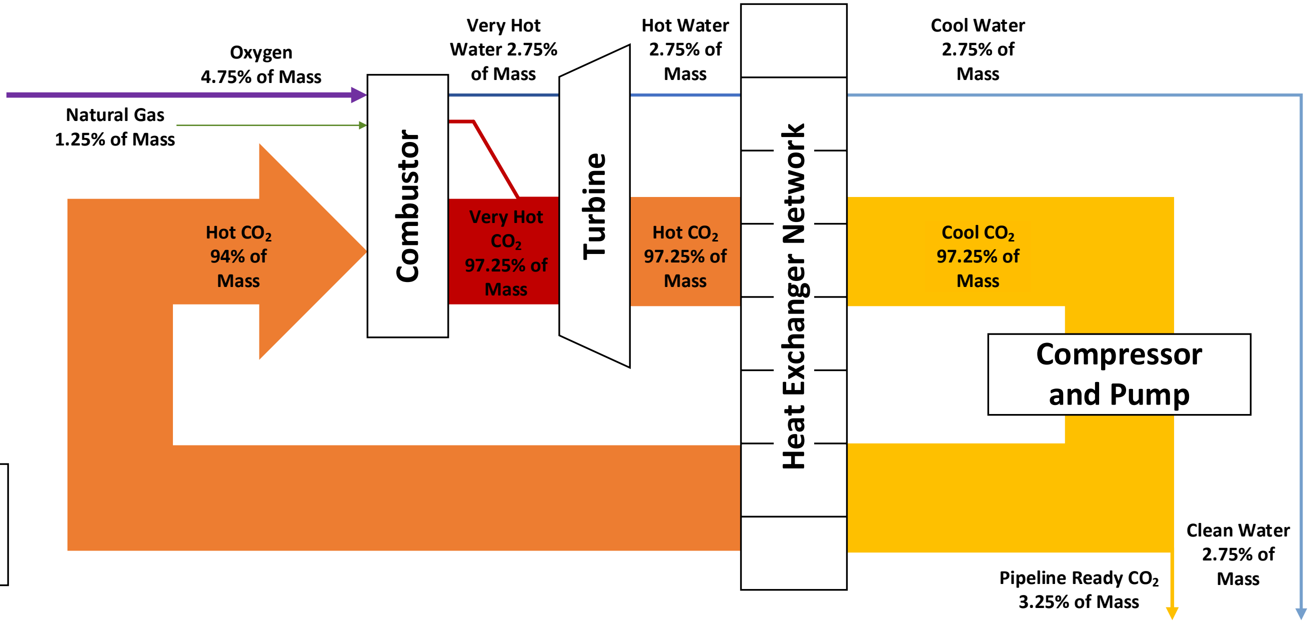
21st Century Power Plant Program

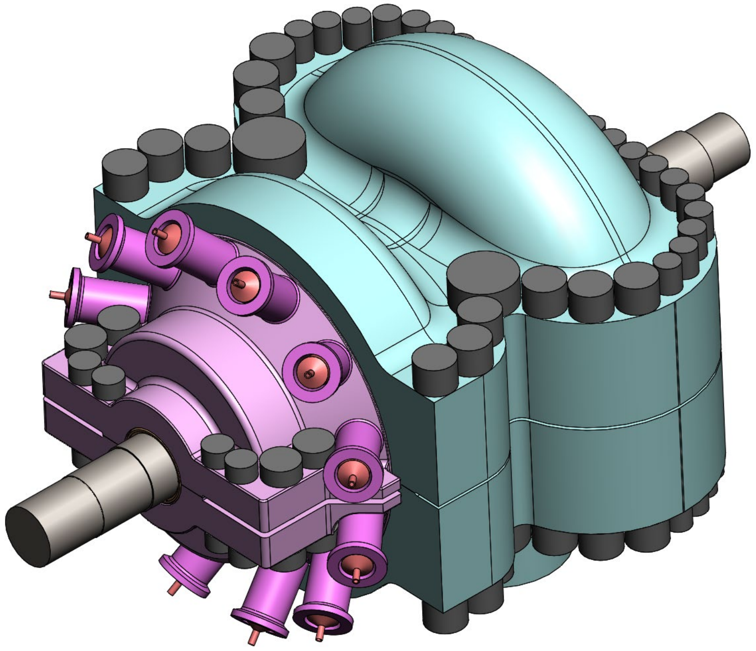
Jeff Moore, Ph.D.

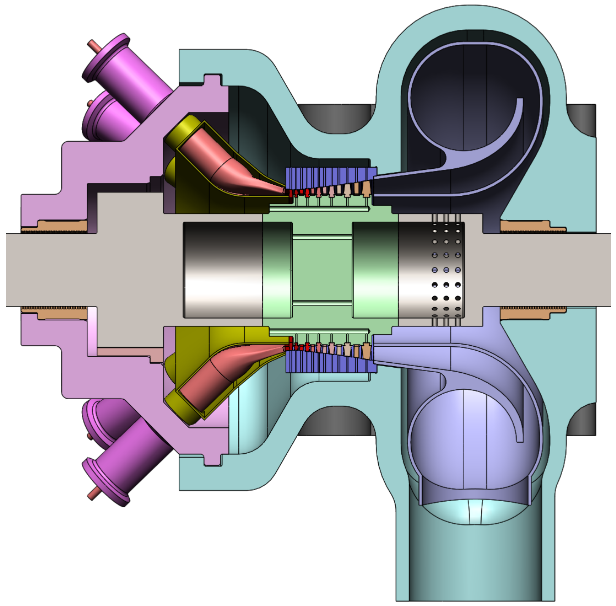
September 28, 2022

Program Overview

- Develop 300 MWe (450 MW Gross) oxy-fuel SCO2 turbine using Allam-Fetvedt cycle with 98% carbon capture using natural gas and coal synthesis gas
    - 1150°C Firing Temperature (775°C Exhaust)
    - 300 bar Inlet Pressure (30 bar Exhaust Pressure)
- Southwest Research Institute (Prime) – 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 Assessmen
- 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 an 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

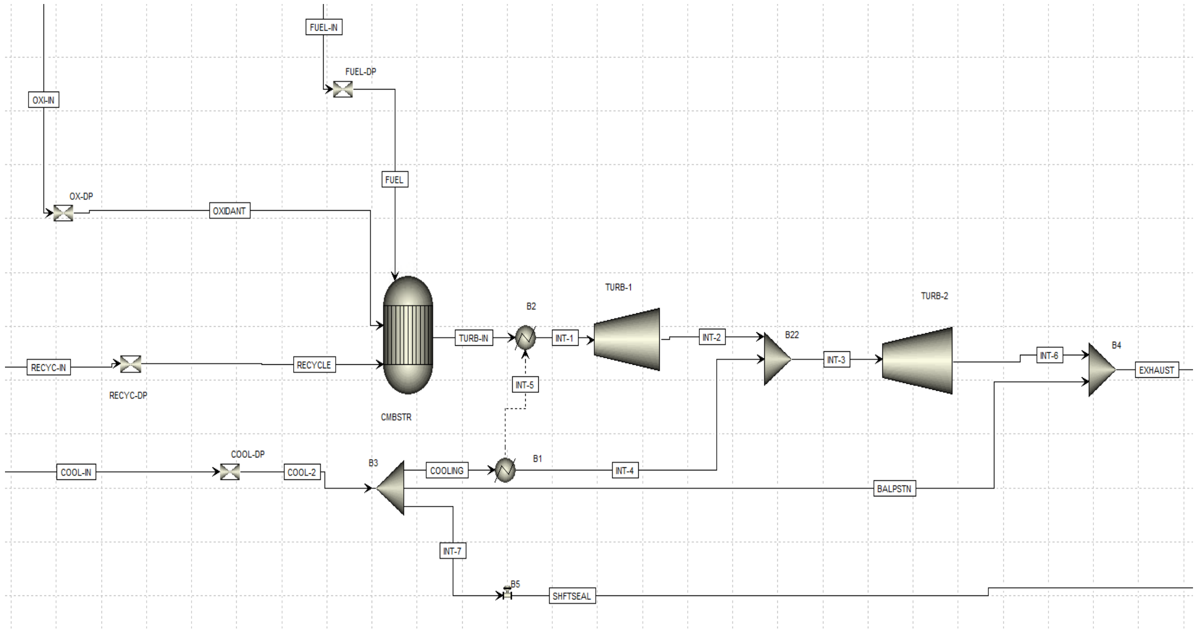






Comparison with NGCC with CCS

Attribute	NGCC	Oxy-Fuel SCO2
Power generator type	NGCC	Allam with O_2 Storage
CCS plant technology	Amine	CO_2 is Working Fluid
Capital cost $/kW	$1481	$1471
Fixed O&M cost $/kW	$48.96	$48.01
Variable O&M cost $/MWh-net	$3.96	$2.66
Fuel Cost $/MWh-net	$45.87	$43.45*80% =$34.76*
Power generator heat rate (kJ/kWh)	7,118	6,743
Power generator LHV net plant efficiency	50.6%	53.4%
Flexibility enabler	n/a	LOX Storage
CO_2 capture rate	90.7%	98.2%

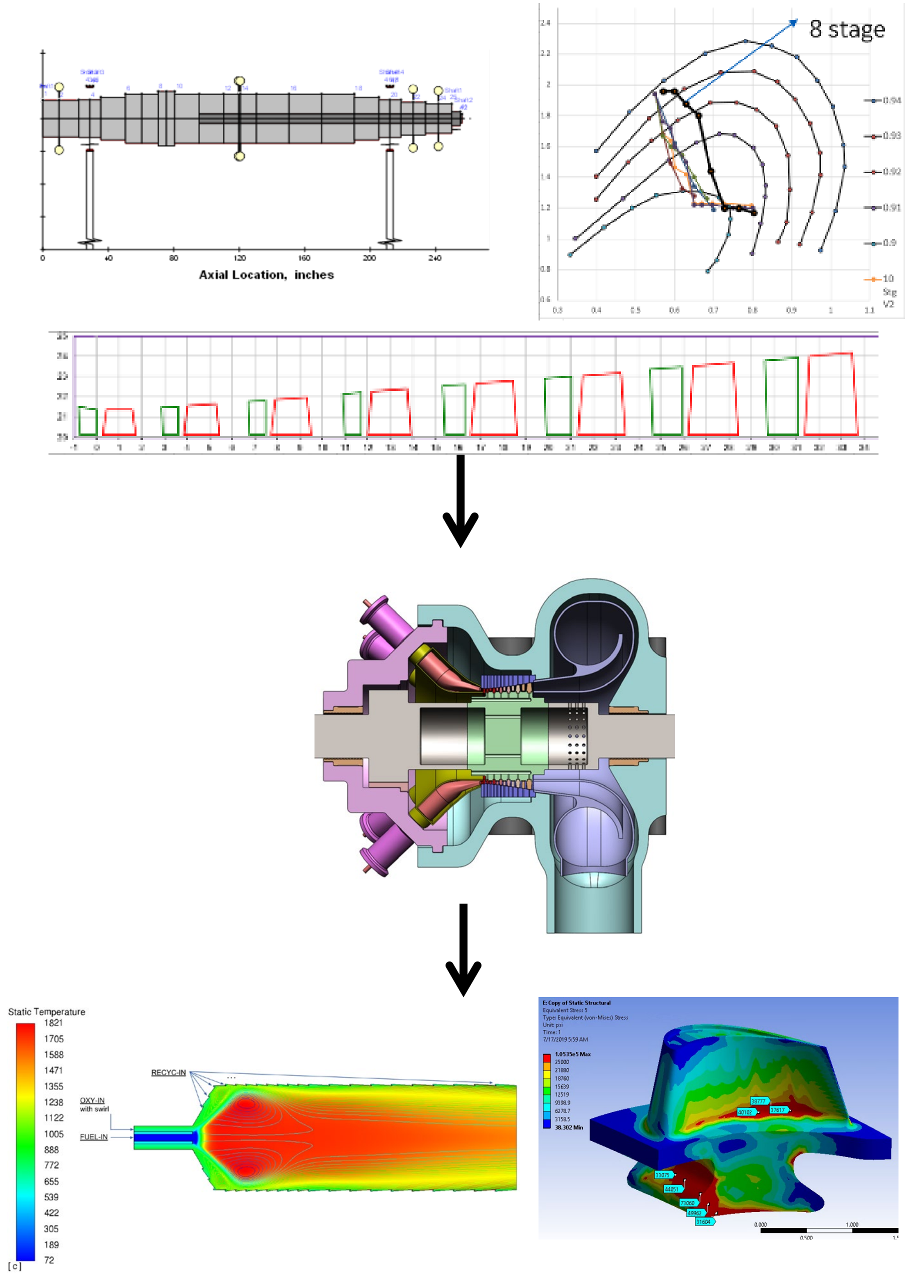


- Turbine Inlet: 305 bar @ 1,150°C
- Turbine Exhaust: 30 bar
- Turbine Power: ~450 Mw_{mech} (300 MWe Cycle)
- Cooling flow supplied to the turbine @ 400°C

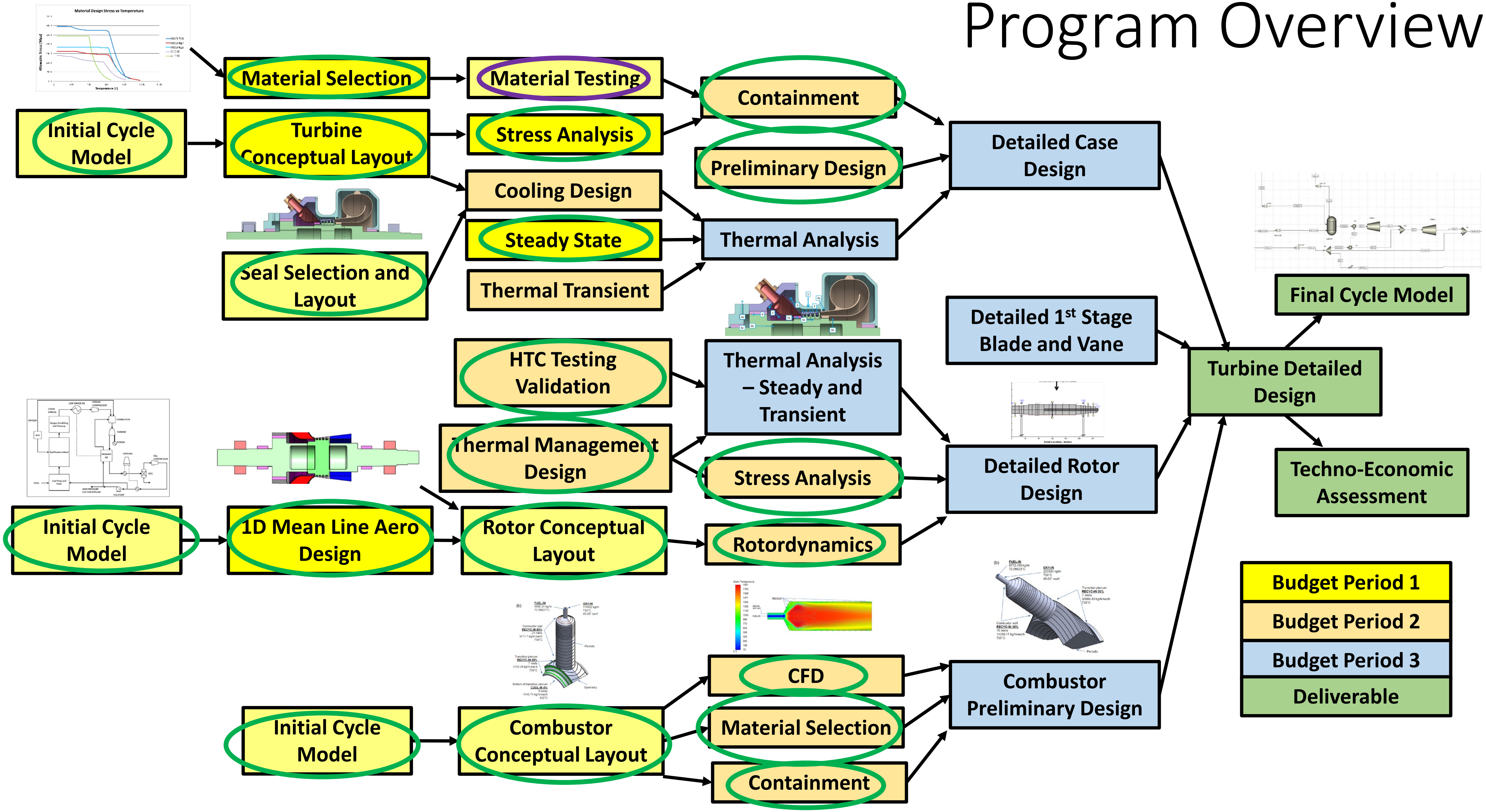
Weiland, N., White, C., 2019, “Performance and Cost Assessment of a Natural Gas-Fueled Direct sCO_2 Power Plant,” NETL-PUB-22274, National Energy Technology Laboratory, U.S. Dept. of Energy, March 15, 2019

Program Overview

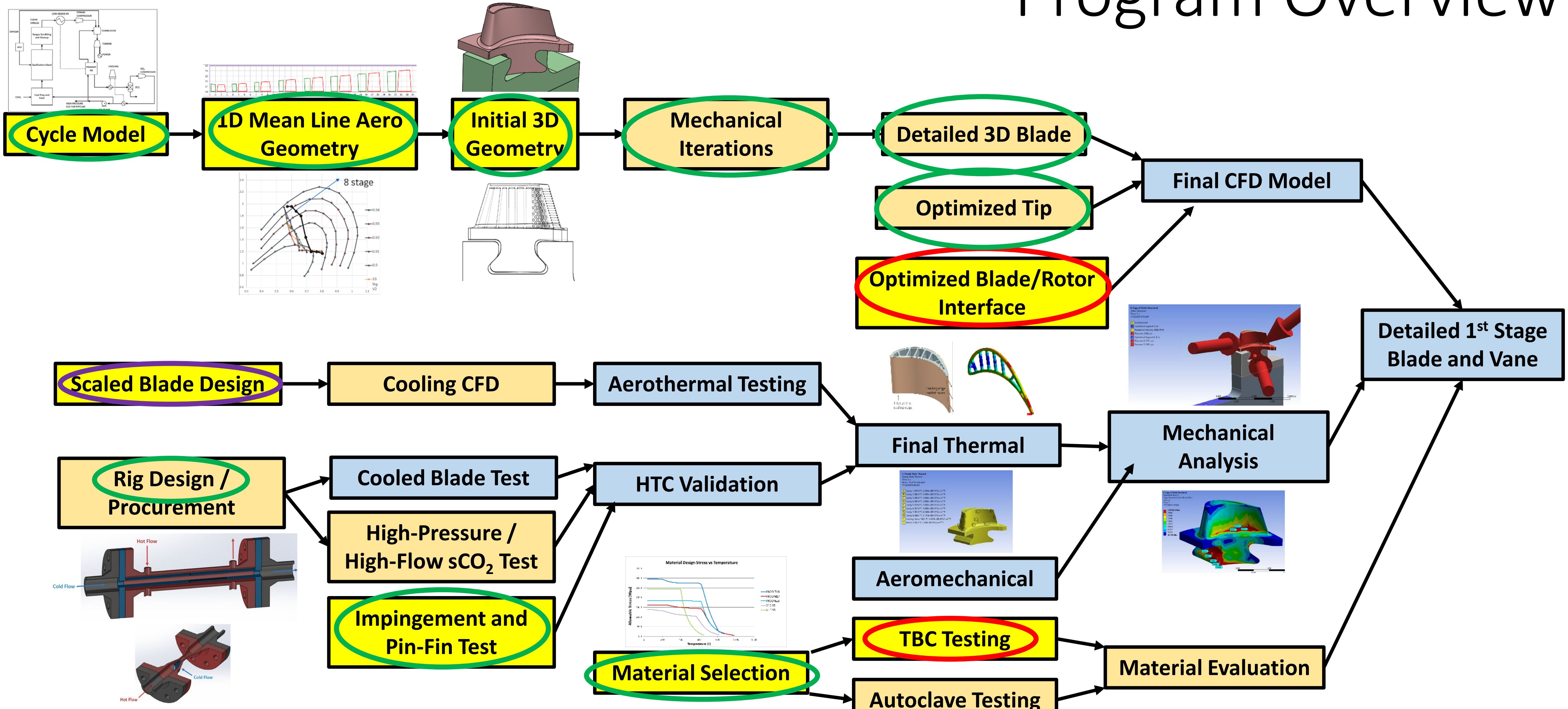
- Three Step Design Approach (3 years)
  - Budget Period 1 – Conceptual Design
    - Turbine case and rotor, aerodynamic flowpath, and combustor layout with initial analysis and calculations to justify that the design can meet cycle requirements
  - Budget Period 2 – Preliminary Design
    - Updated 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



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

BP2 – Technical Summary

- ***Task 2.1 – Heat Transfer Testing***
  - *Subtask 2.1.1: High Reynolds Number sCO_2 Rig Manufacturing*
  - *Subtask 2.1.2: High Reynolds Number sCO2 Testing*
  - *Subtask 2.1.3: Design of Test Blade for Thermal Validation*
  - *Subtask 2.1.4: Impingement and Pin-Fin Testing with sCO2*
- ***Task 2.2 – Turbine Preliminary Design***
  - *Subtask 2.2.1: Optimize Turbine Tip*
  - *Subtask 2.2.2: Update Blade Design*
  - *Subtask 2.2.3: Scaled Up Test Blade Design*
  - *Subtask 2.2.4: Scaled Up Blade Procurement*
  - *Subtask 2.2.5: Preliminary Case and Rotor Layout*
- ***Task 2.3 – Autoclave Material Testing***
  - *Thermal Cyclic Testing at 780°C in Ambient Air*
  - *High Pressure/Temperature Material Autoclave Testing in sCO2*
- ***Task 2.4 – Updated Syngas Combustion Cycle***
- ***Task 2.5 – Initial Techno-Economic Assessment***

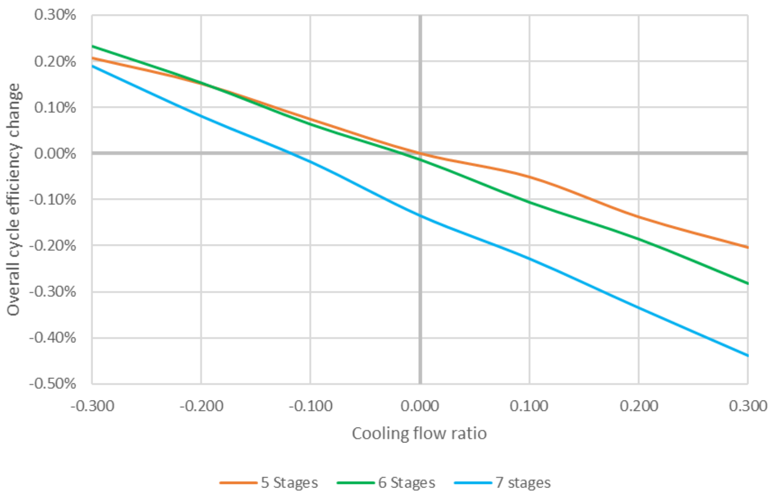
Task 1.2 – Cycle Model-8 Rivers

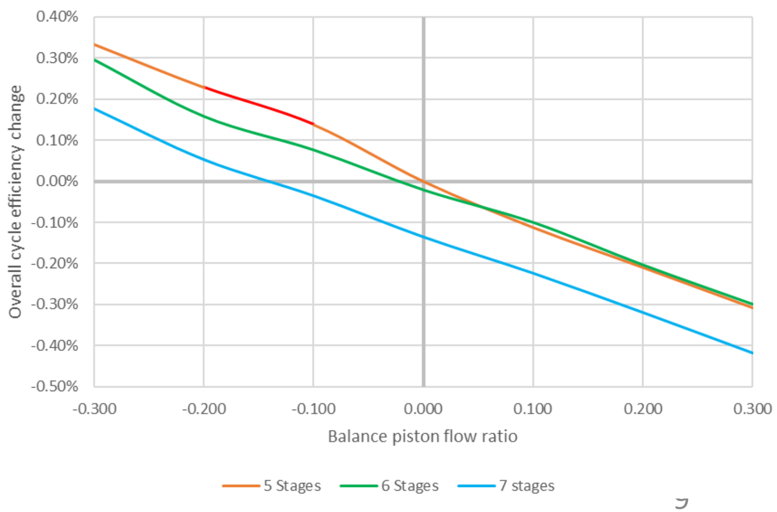
- Two main impacts on cycle model when compared to a Natural Gas Oxy-Combustion Cycle
  - Addition of Gasifier and Syngas Cleanup. These impact the overall cycle performance as they are a direct efficiency loss. Turbine parameters are held constant (Inlet temperature, pressure, and volume flow). This 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%
- Turbine Design Conditions:
  - Flow rate: 30,000 m^3/hr
  - Pressure: 315 bar
  - Temperature: 1150C

    706C Recycle Flow sections

    <780C Exhaust
  - 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%

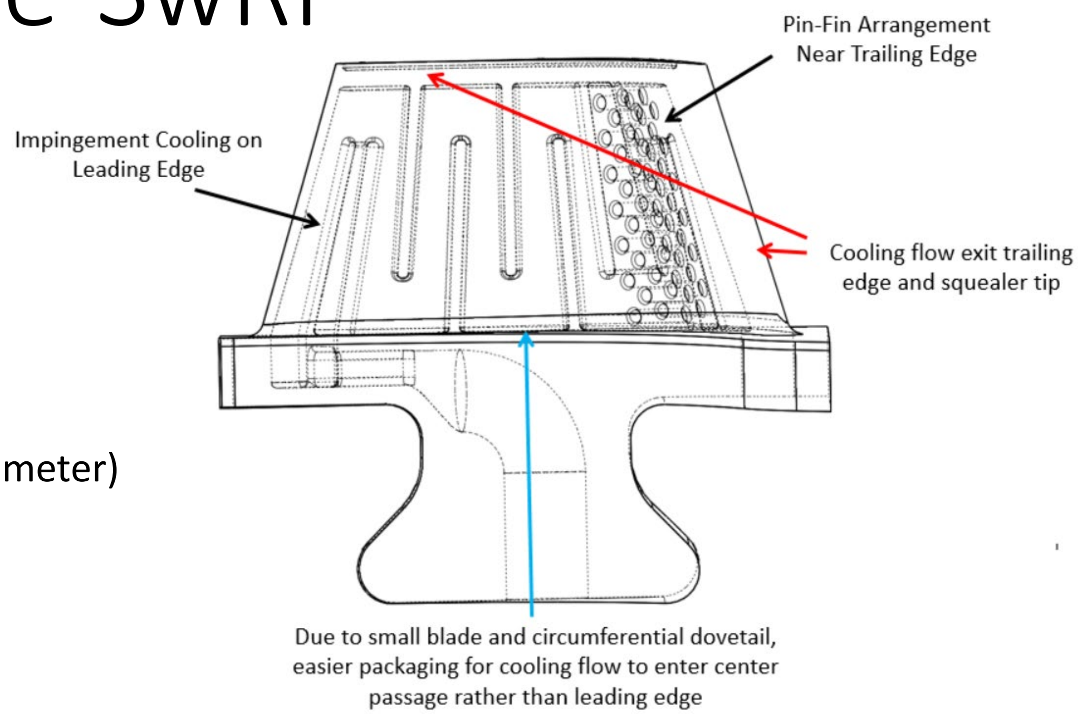


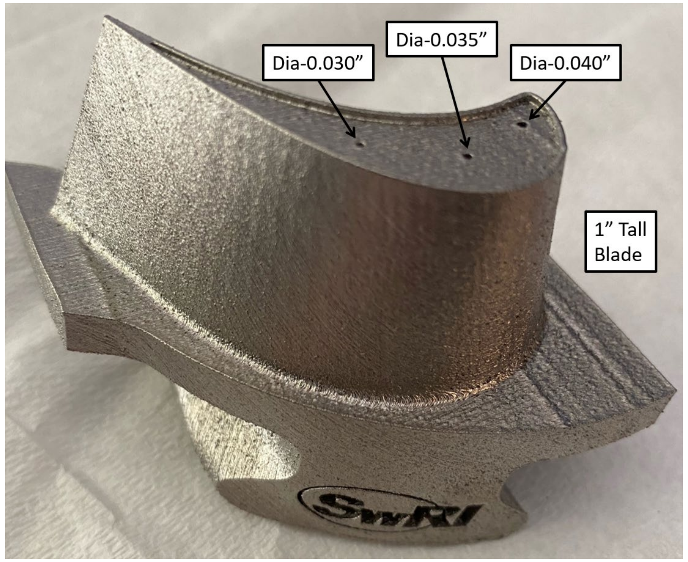


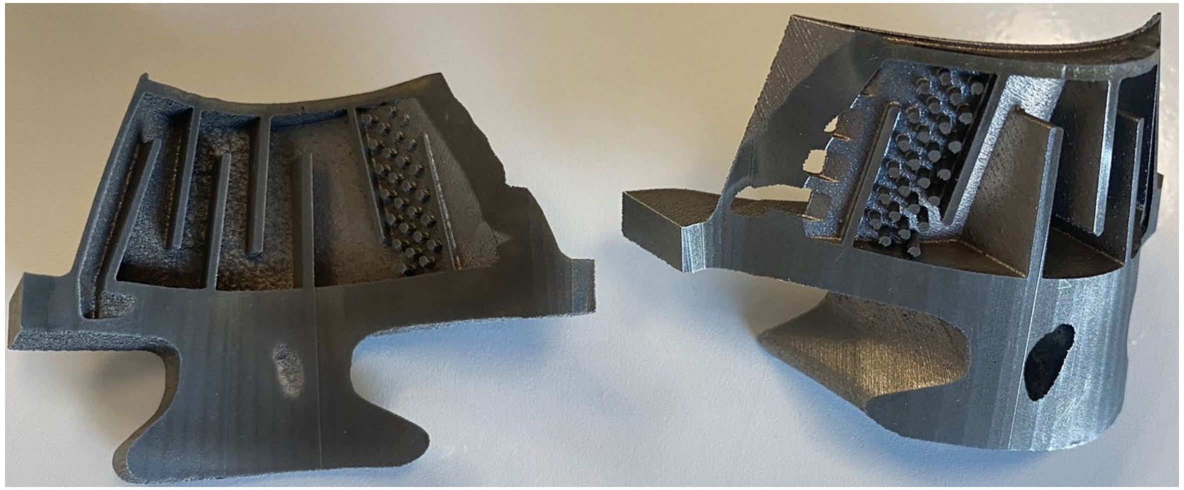
Internally Cooled Turbine Blade-SwRI

<u>Impingement and Pin-Fin Assessment</u>

- Evaluate potential areas for various heat transfer enhancements (pins, fins, impingement, serpentine, surface roughness)
- AM Manufacturing Concerns
    - Internal surface roughness?
    - Accuracy of internal features (pins, fins, serpentine)
    - Minimum diameter for impingement cooling holes (Trial Prints → 0.030” Diameter)
    - Creep life and LCF
- Trial print with IN718 demonstrated successful feature generation including turbulator ribs, pin-fins, and squealer tip holes



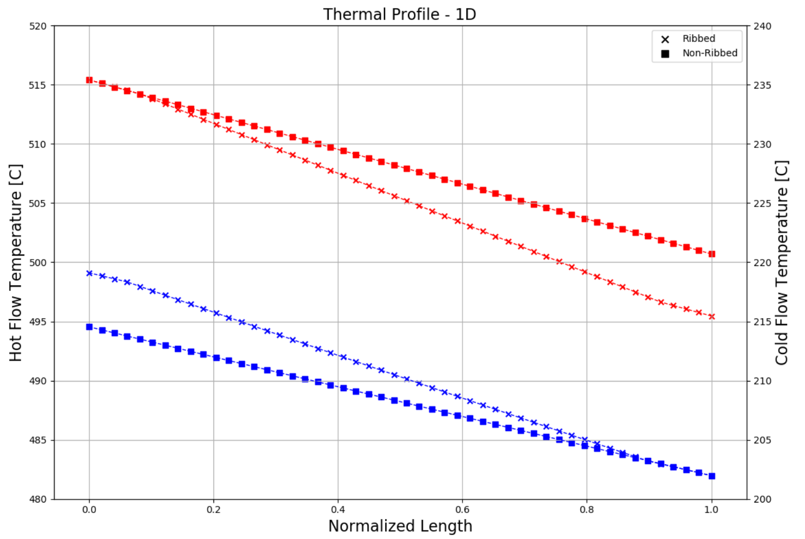


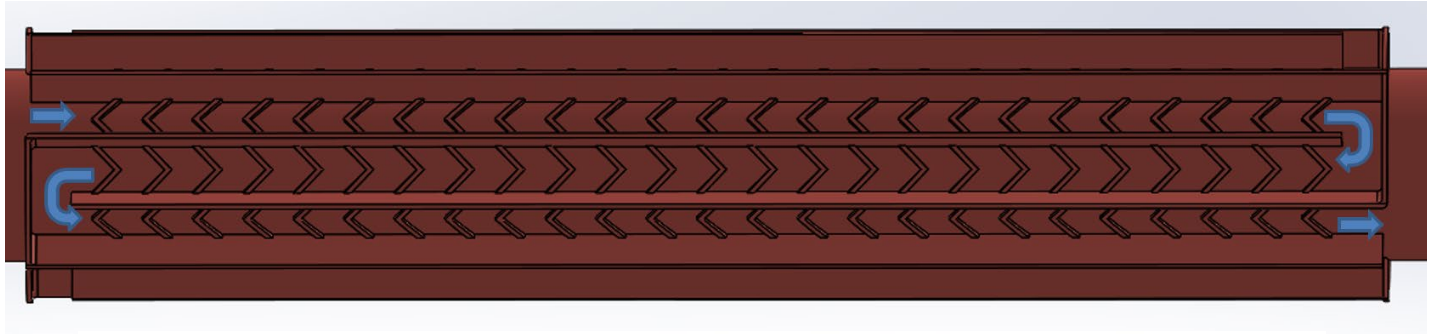


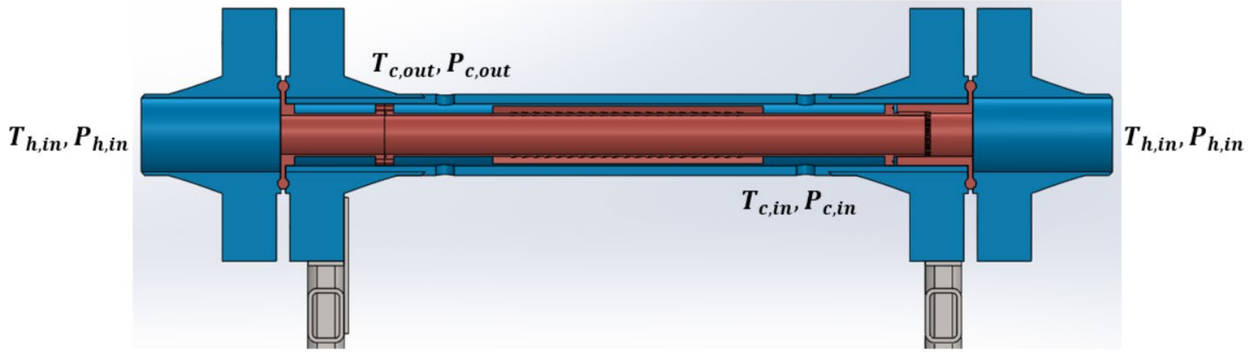
Task 2.1 – Heat Transfer Validation-SwRI

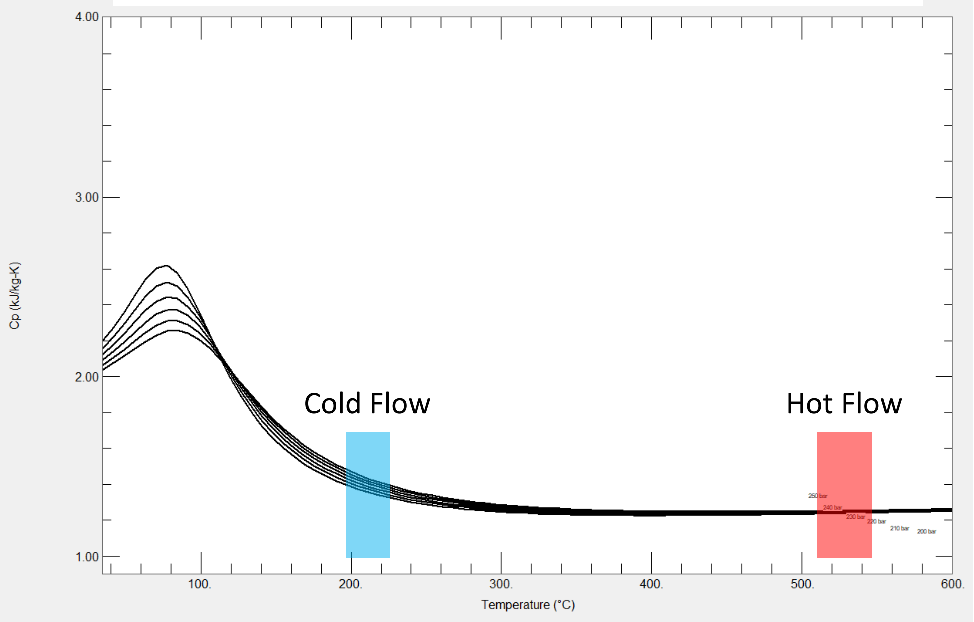
Task 2.1.1 – High Reynolds Number sCO_2 Test Rig Design

- Design a high flow sCO_2 heat transfer rig that can evaluate different types of internal HTC enhancements for blade cooling flow
- For a 1st stage sCO_2 turbine blade, expected RE numbers through mid-section cooling passages are in the 400,000 range (current gas turbine correlations limited to 200,000)
- Literature on ribbed passages experimental data indicates a decrease in Nusselt number enhancement (ribbed vs. plain wall) with increasing RE number, yet do not extend to the applicable range.
- Utilizing the high temperature sCO_2 flow loop at SwRI, testing will provide performance comparison of serpentine passage features and static blade thermal validation.



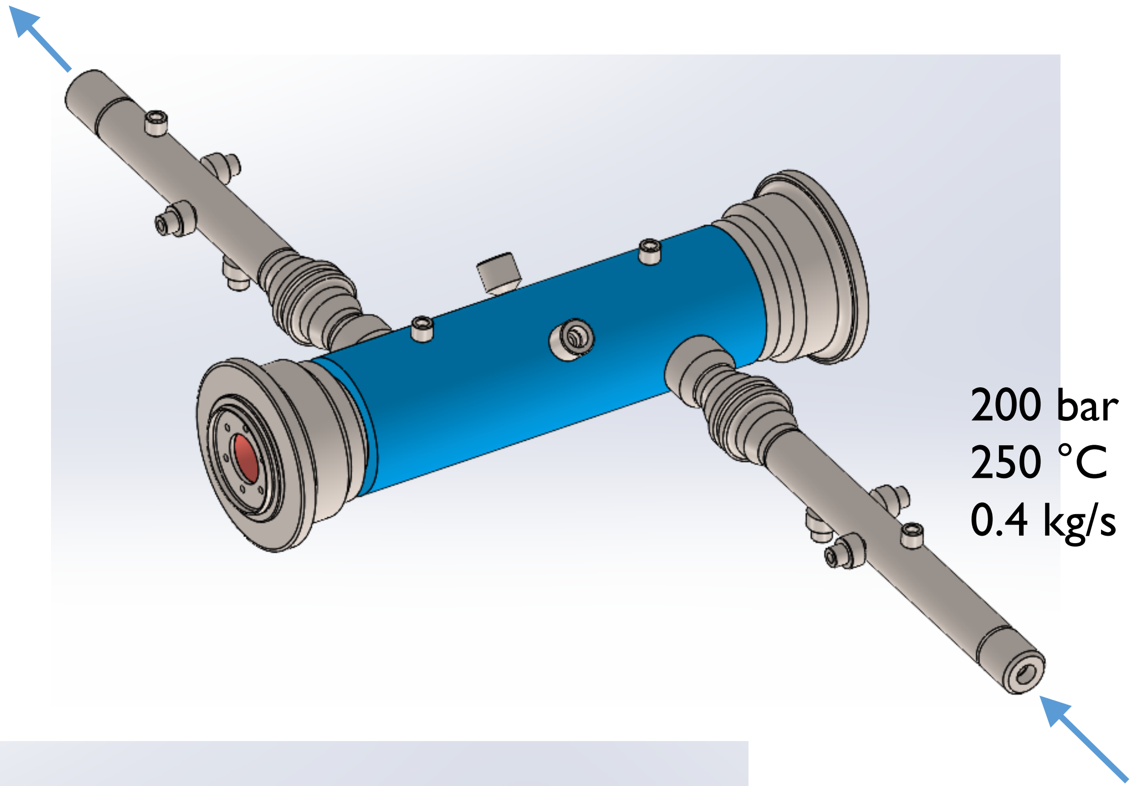






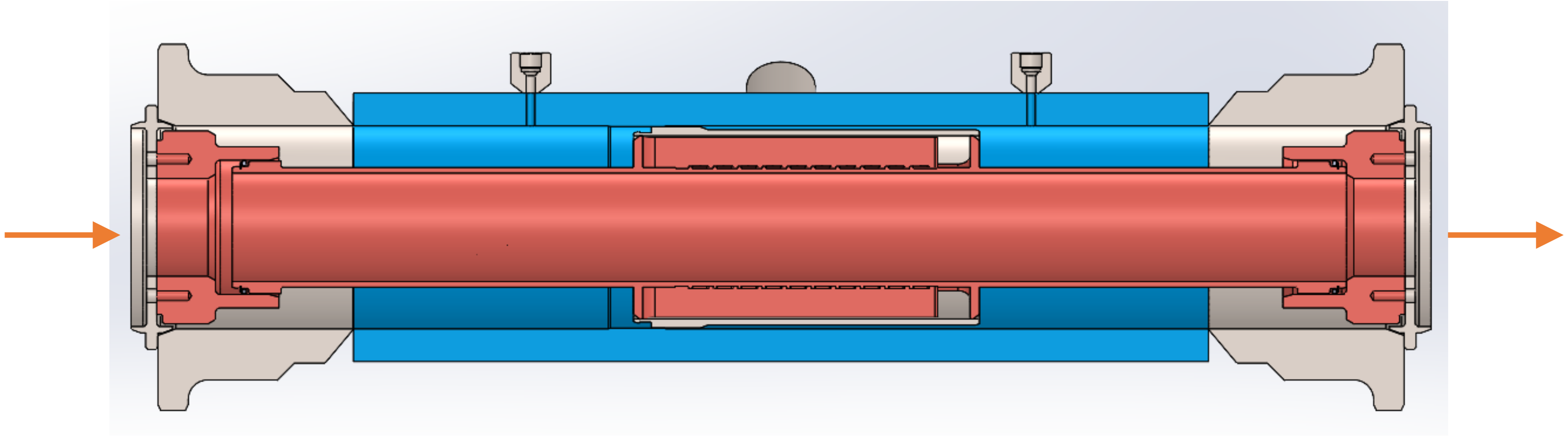
Heat Transfer Rig

- Case contains cool flow in outer annulus serpentine passages, with internal heater outlet flow in the countering direction.
- Inlet and outlet ports include multiple RTD measurements, as well as dP measurements across passage section.



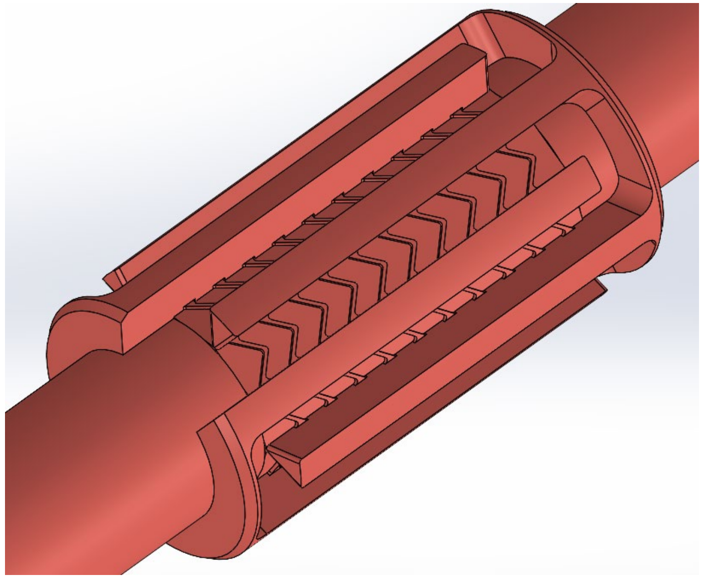
200 bar
250 °C
0.4 kg/s

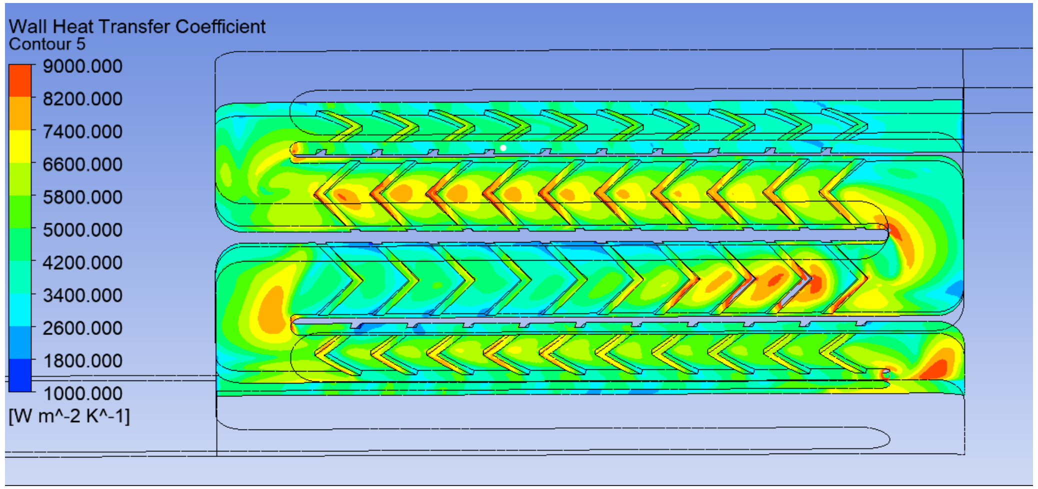
200 bar
500 °C
1.8 kg/s



Heat Transfer Rig – Insert Design

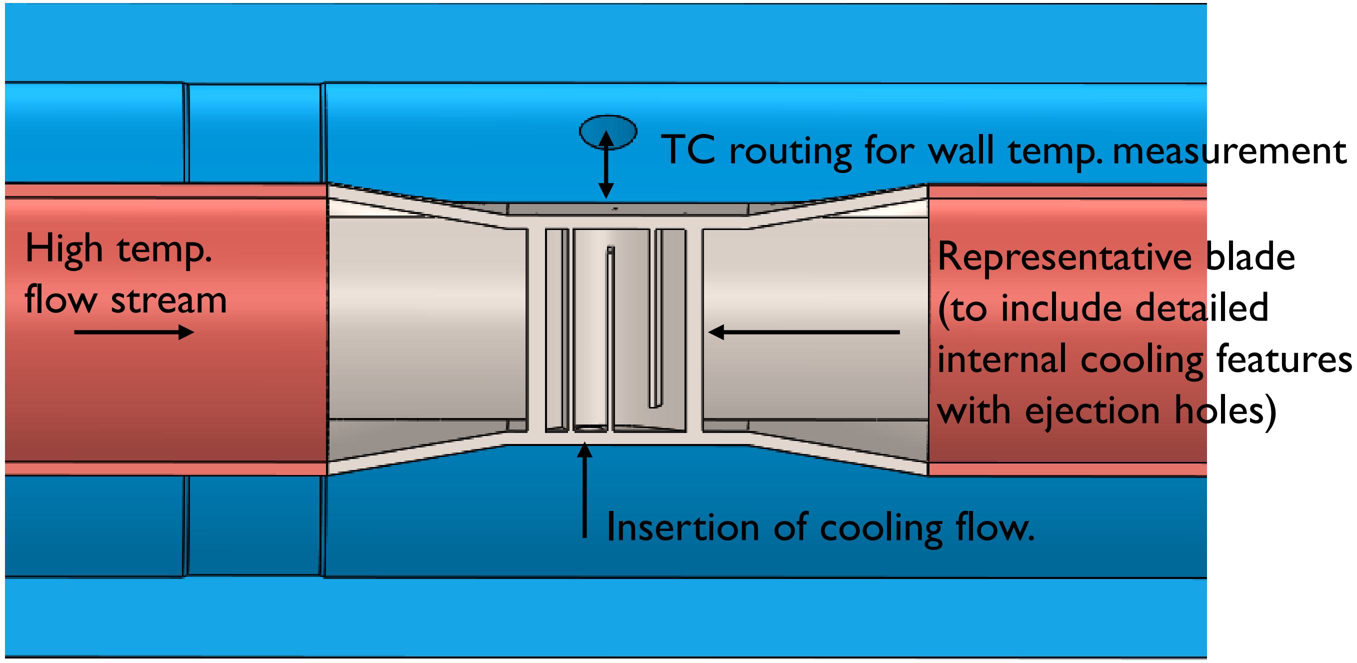
- Symmetric flowpaths include 5 passes (AR: 1) with chevron ribs, according to design rules for blade cooling passages.
- CFD simulations were run to compare ribbed and plain wall geometries.
  - For prediction of overall HTC, 36% higher for ribbed passages vs. plain wall.
- Inserts are interchangeable in the test section, with inclusion of sealing surfaces to prevent leakage flow.
- All rig components have been released for machining and fabrication.





Subtask 2.1.3: Design of Test Blade for Thermal Validation-SwRI

- BP3 will reuse existing case and components to test the detailed design of the 1st stage blade, with minor modifications for instrumentation purposes to measure wall temps.
- Validate CHT CFD models of blade



Subtask 2.1.4: Impingement and Pin-Fin Testing with sCO2

Team:

Jay Kapat

Erik Fernandez

Ryan Wardell (PhD Student – Pin Fin Heat Transfer Simulation)

Marcel Otto (PostDoc – Pin Fin Design)

John Richardson (MS Student – Impingement Rig Fabrication and Testing)

Matt Smith (Integrated BS-to-MS student – Pin Fin)

UCF High-Temperature/Pressure sCO2 Heat Transfer loop

- The UCF heat transfer loop is heated through a combination of electrical rope heaters and Joule heated sections
- Heat rejection is achieved through a recuperator, high-flow air cooler, and a chilled water system.

Capability

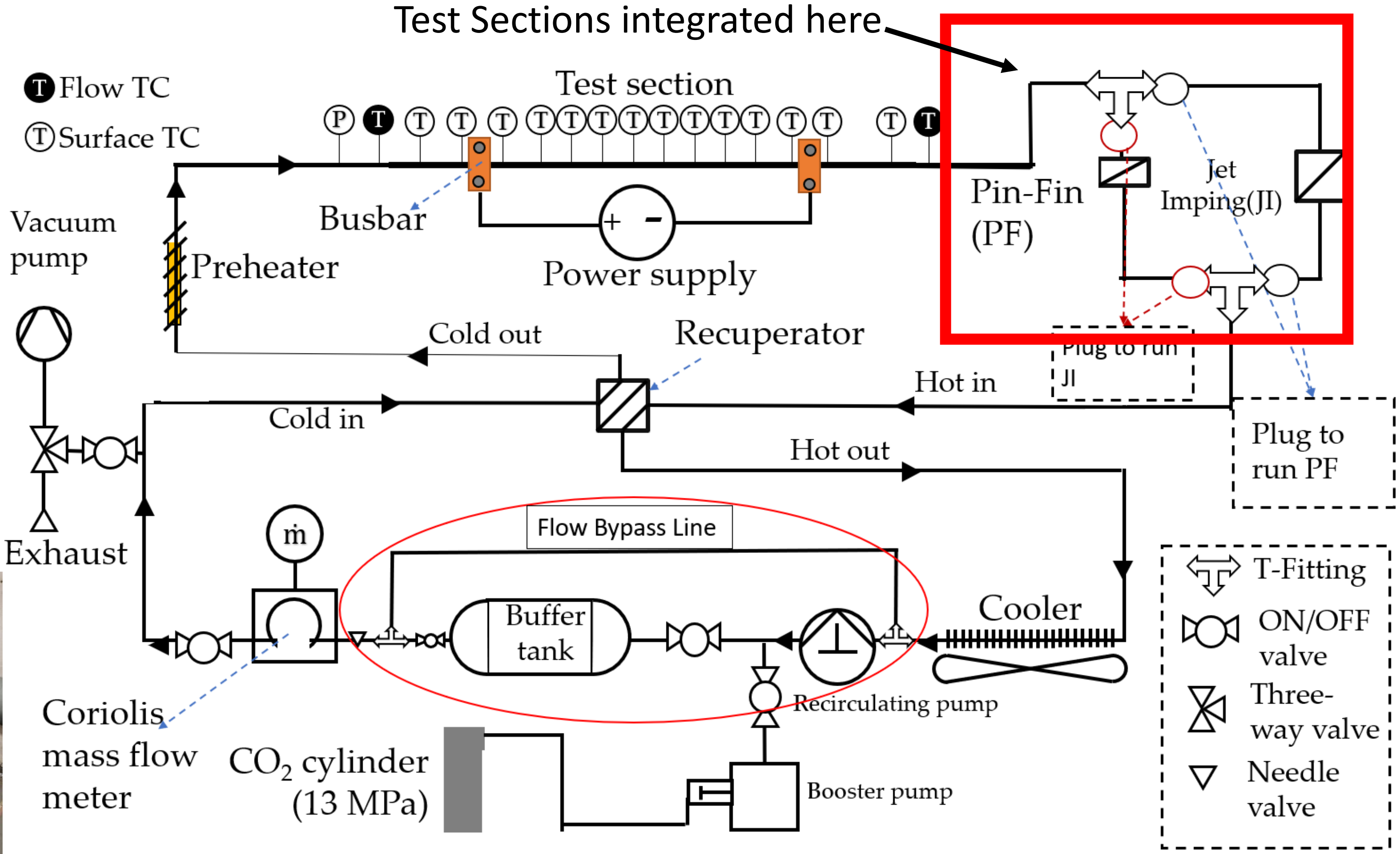
Pressure range: 80 Bar to 260 Bar

Flow Temperature range: 30C to 550C

Wall Temperatures up to 700C for Inconel

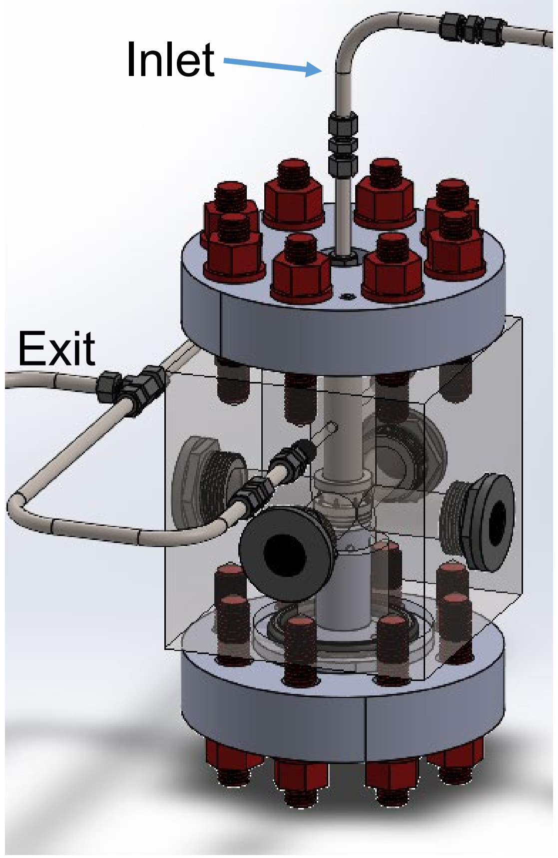
Flow rates up to 0.25 kg/s

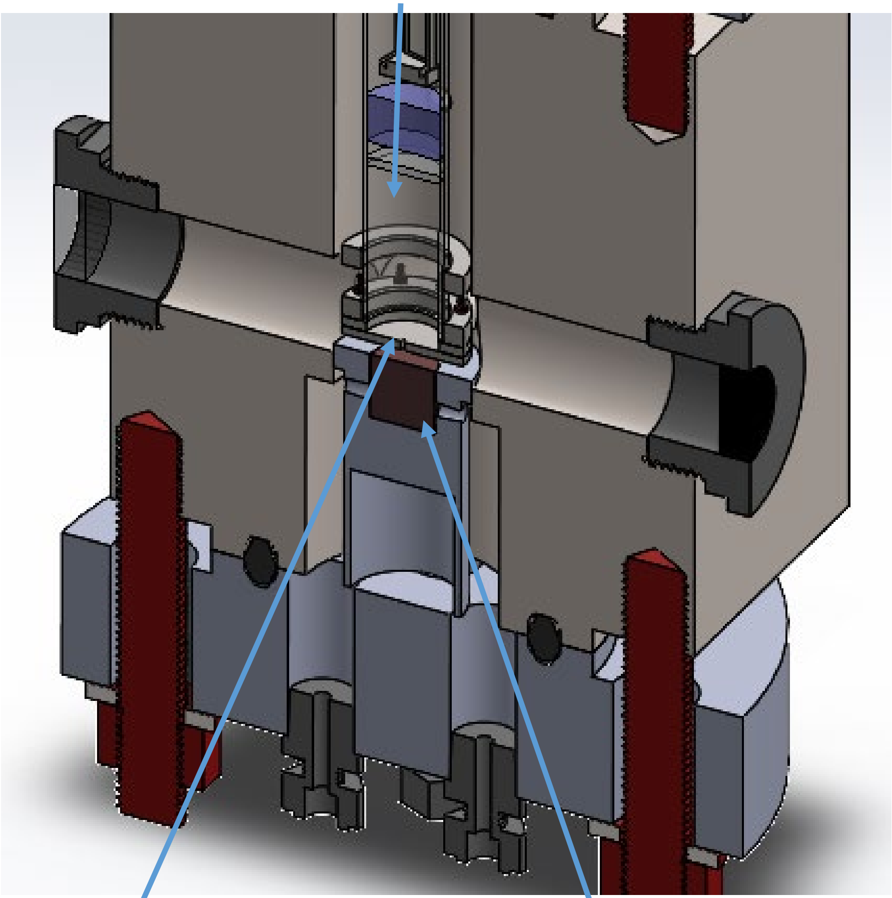
Insulated flow loop in aluminum enclosure, Circulating pump, and recuperator in the loop



sCO_2 Impingement Heat Transfer – Test Section

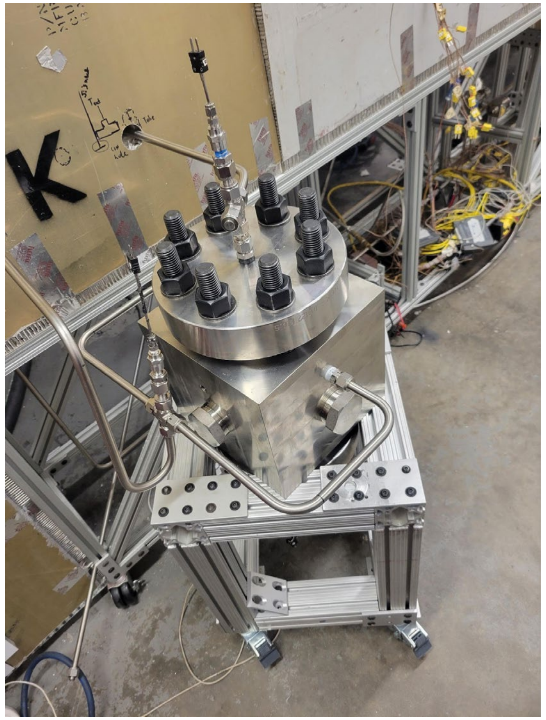
- 316 Stainless steel forging with flanges act as pressure vessel
- Maximum operating pressure 200 bar
- Maximum operating temperature 450°C
- Maximum Mass Flow Rate: 0.2 kg/s
- Instrumentation for heat transfer coefficient estimation
- High pressure gland fittings for power transmission and instrumentation
- Variable orifice diameter (> 1mm)
- Variable jet to target spacing
- Copper Impingement target diameter 1.5 in
- Capability for optical diagnostics

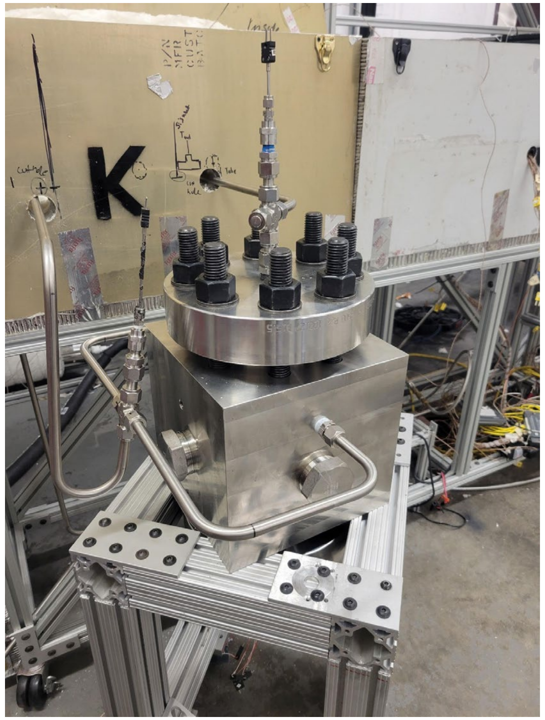




sCO_2 Impingement Heat Transfer – Hardware

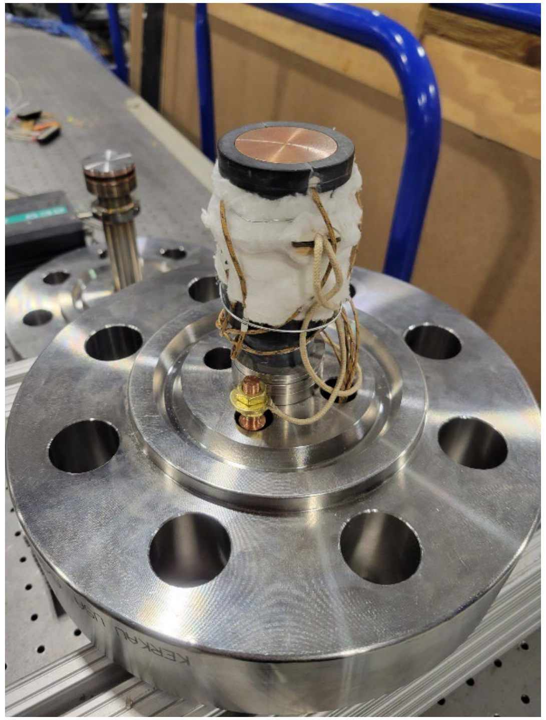
- Heat transfer feature assembly includes a copper block with embedded thermocouples and a high-temperature Mica heater
- Instrumentation and power are transferred through the high-pressure vessel through Conax gland fittings
- Final testing assembly is fully wrapped in ceramic insulation to minimize heat loss





Main Rig Assembly as integrated into flow loop

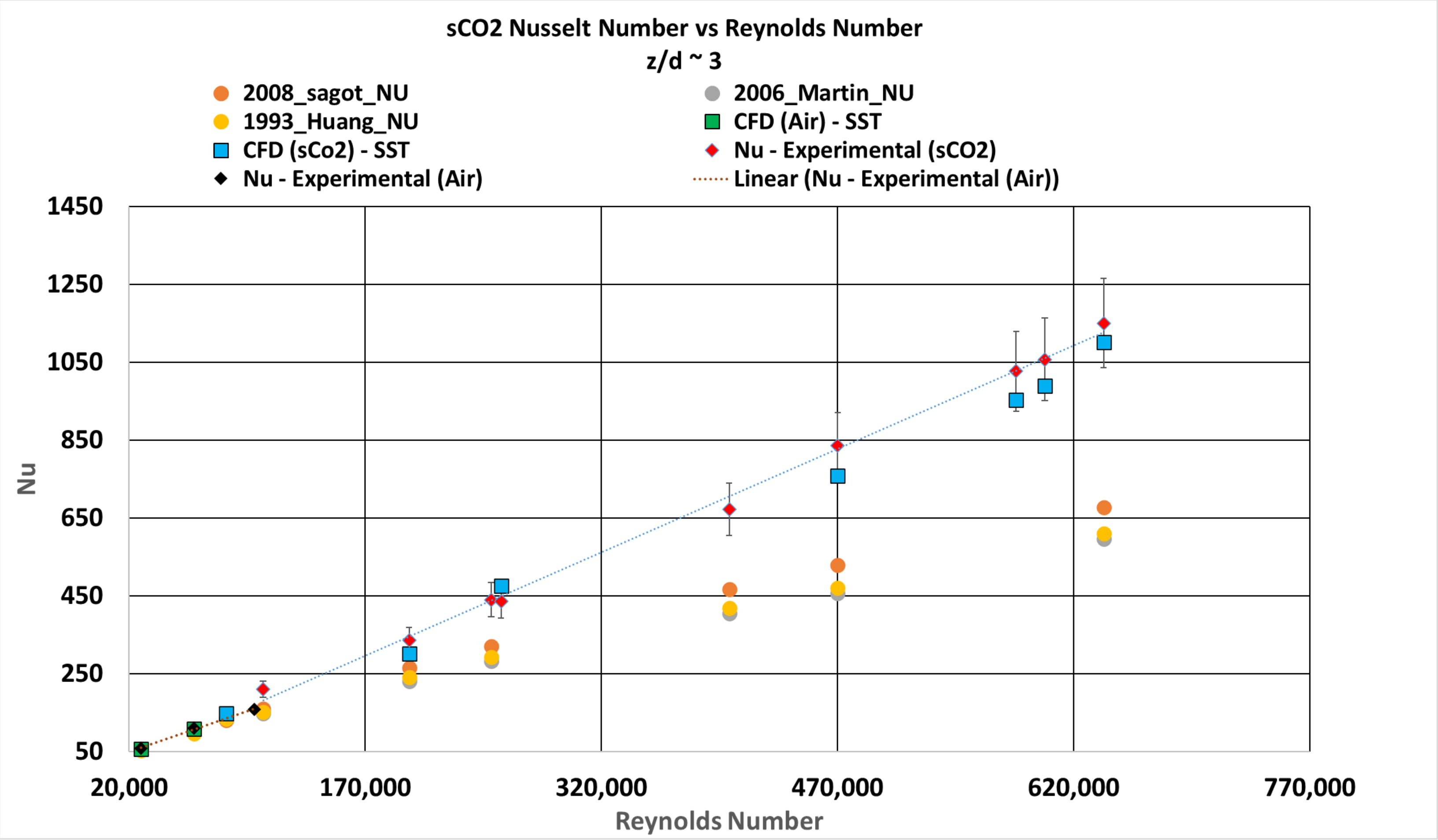
Jet plenum and orifice assembly



Heat transfer feature assembly with heater and instrumentation

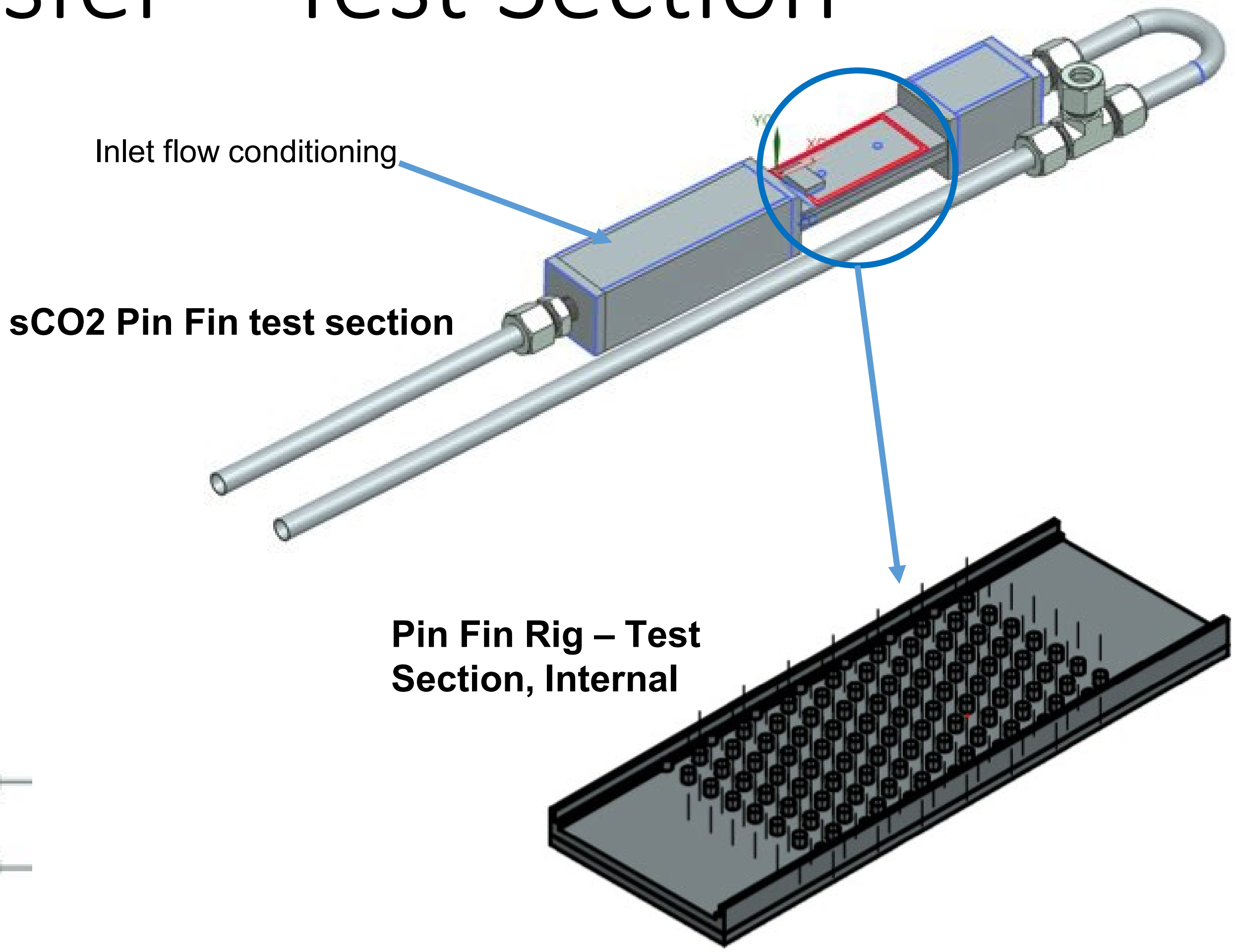
sCO_2 Impingement Heat Transfer – Results

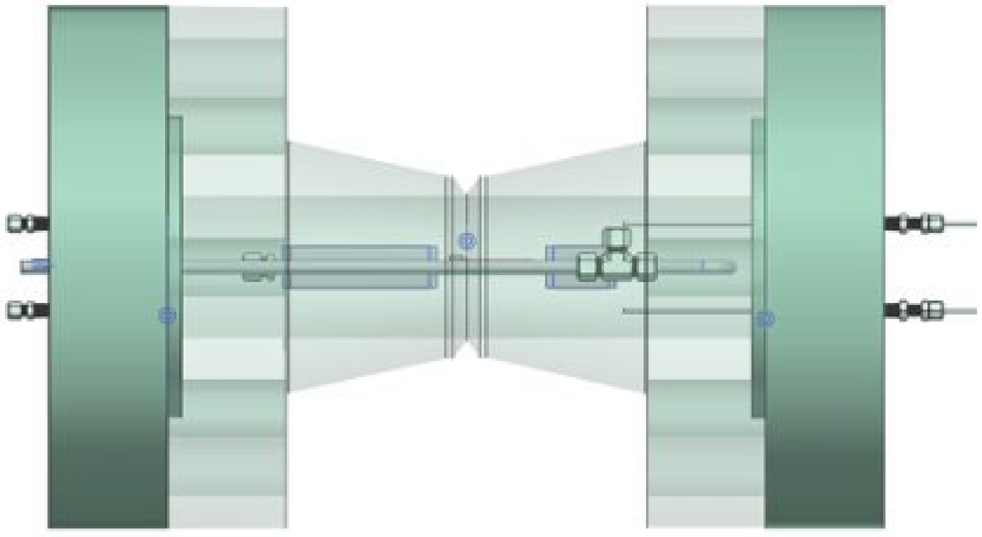
- 14 cases were run, covering jet Reynolds numbers between 86,000 - 913,000, inlet pressures between 100 bar - 210 bar, and inlet temperatures between 104C - 450C. (Note: data shown in red symbols are for the project test conditions only)
- Companion CFD was run for various air and sCO_2 cases, and show reasonable agreement with test data (square symbols)
- Air-derived impingement heat transfer correlations drastically underpredict sCO_2 heat transfer
- While the Nusselt number trend with Reynolds number is linear, as with air, the differing slopes ***demonstrate these correlations cannot be used with sCO_2 as the working fluid***



sCO_2 Pin-Fin Heat Transfer – Test Section

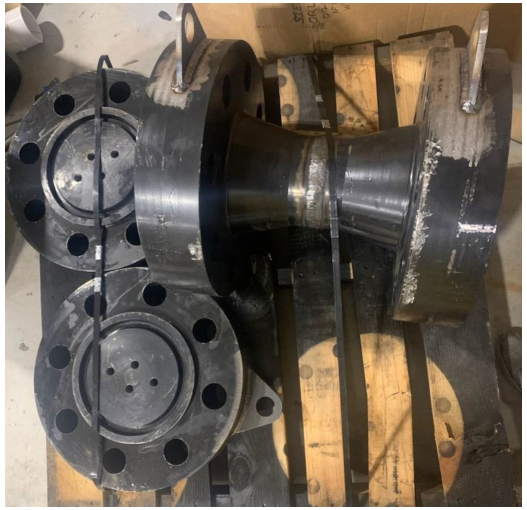
- Pin Fin test section, housed within steel pressure vessel
- Maximum operating pressure 200 bar
- Maximum operating temperature 450°C
- Maximum Mass Flow Rate: 0.2 kg/s
- Instrumentation for pin fin array averaged heat transfer coefficient estimation
- High pressure gland fittings for power transmission and instrumentation
- 14 pin rows in test section. Geometry based on Ames pin fin study
- Wall heating via high temperature Mica Heaters



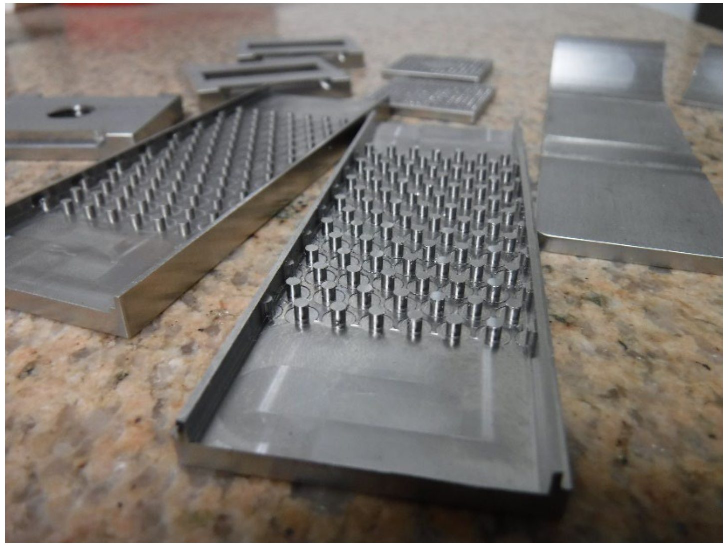


Test section pressure vessel

sCO_2 Pin-Fin Heat Transfer – Hardware



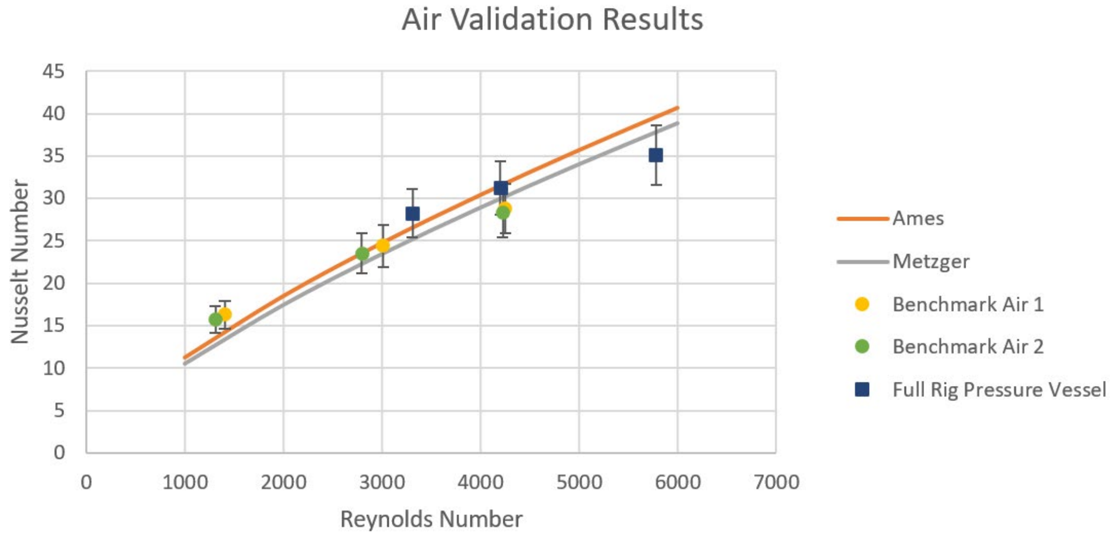
Pressure Vessel

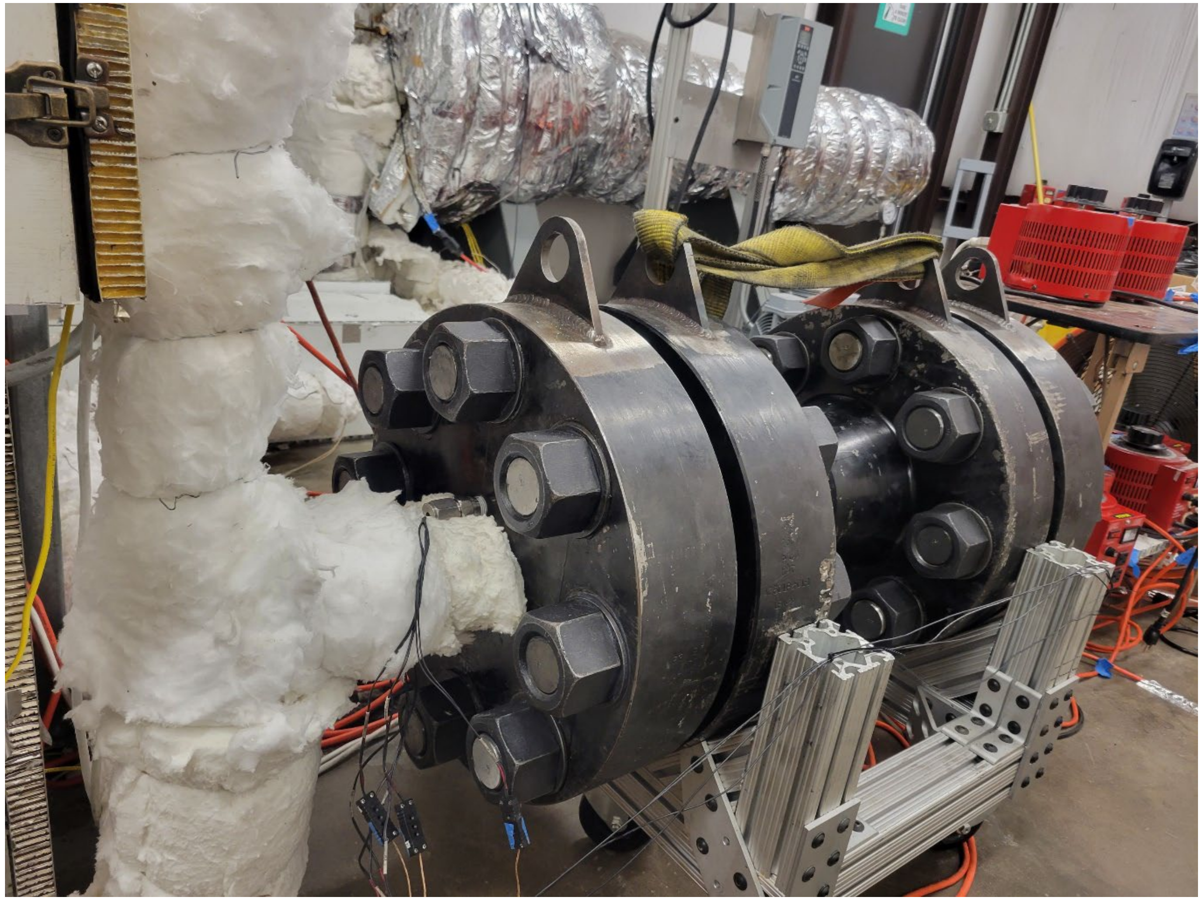


Internal Stainless Steel Test Section Parts Prior to Welding
Note: Pin-Fin Channel height = 4mm, with 2mm Diameter Pins

sCO_2 Pin-Fin Heat Transfer – Integration and Testing

- Pin-Fin heat transfer rig has been integrated into the main heat transfer loop and testing is on-going
- Prior to rig testing, vessel was hydrotested according to the ASME Section VIII-1 procedure (tested up to 408 Bar)
- Before sCO2 testing, the rig was run with air as the working fluid, and heat transfer results were compared to air correlations, to validate performance. This procedure was also done on the impingement heat transfer rig
- Testing campaign is scheduled to conclude in mid to late October





Pin-Fin Heat Transfer rig integrated into sCO2 loop

Task 2.2 – Turbine Preliminary Design

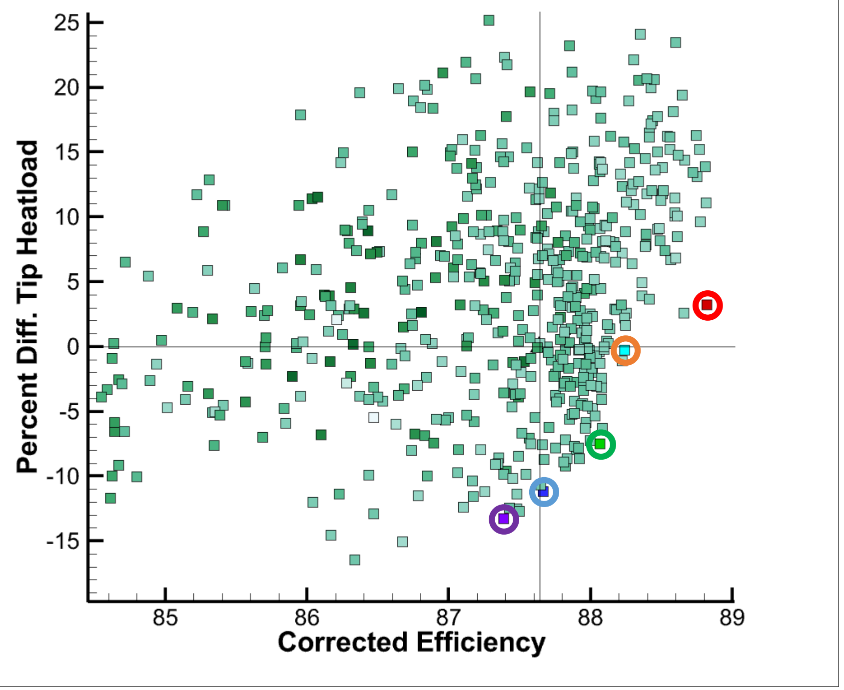
Subtask 2.2.1: Optimize Turbine Tip

Subtask 2.2.2: Update Blade Design

Subtask 2.2.3: Scaled Up Test Blade Design

Subtask 2.2.4: Scaled Up Blade Procurement

Subtask 2.2.1: Optimize Turbine Tip

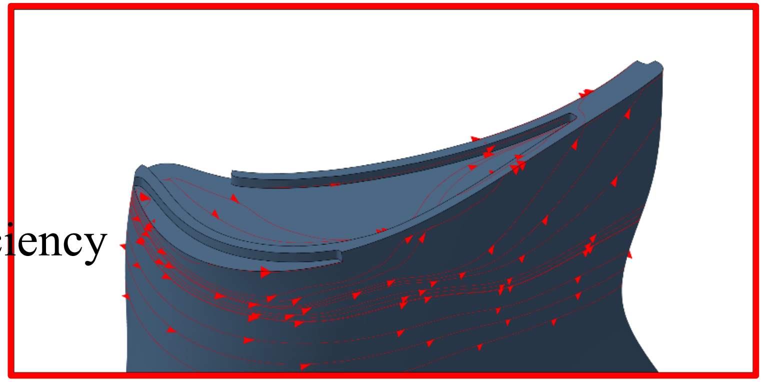


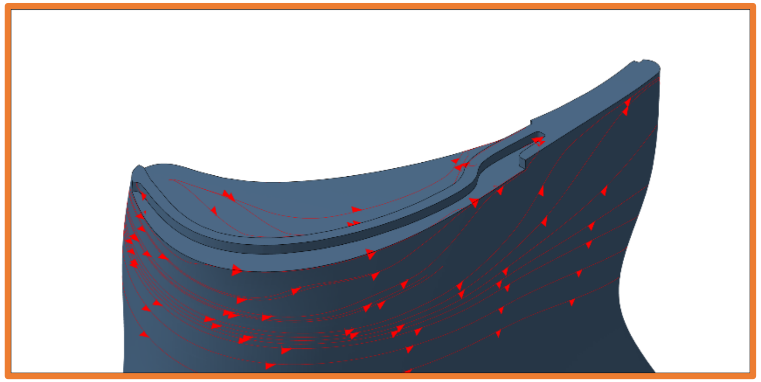
	$\Delta\eta_{isen\_corr}$	Δ Tip Heat Load (W)	Δ Total Heat Load (W)	Δ Mass flow (kg/s)	Δ Torque (Nm)
Squealer	87.63%	3583	37882	921.15	1289
P17_IND020	1.19%	3.23%	1.26%	-0.01%	1.92%
P15_IND019	0.61%	-0.28%	1.56%	-0.01%	1.64%
P13_IND024	0.43%	-7.50%	0.82%	-0.13%	0.82%
P13_IND014	0.03%	-11.15%	1.07%	0.10%	0.55%
P17_IND022	-0.25%	-13.27%	0.62%	0.11%	0.08%

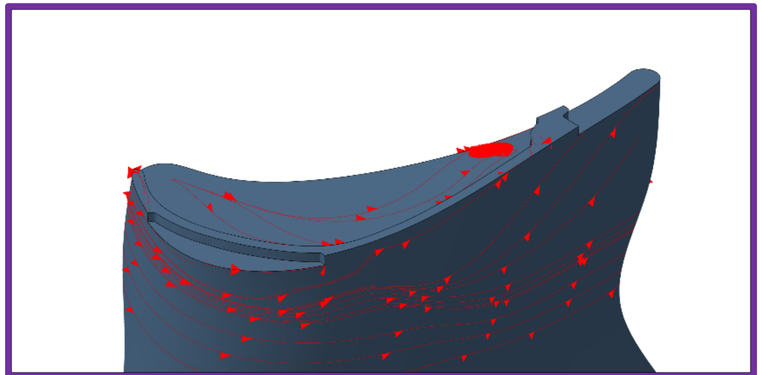
550 Individuals grouped among 18 populations

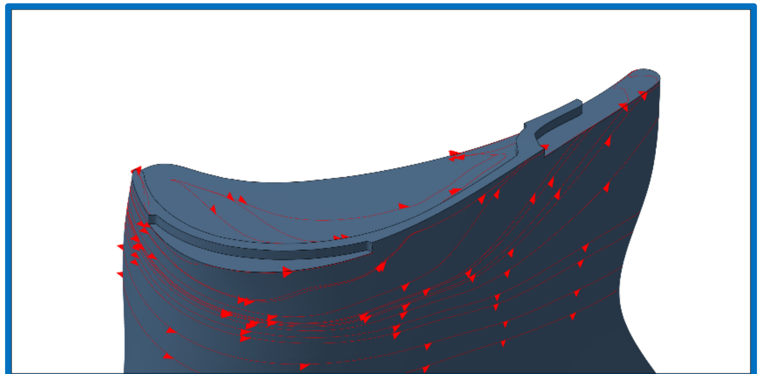
Trade-offs between Heat load and Corrected Efficiency

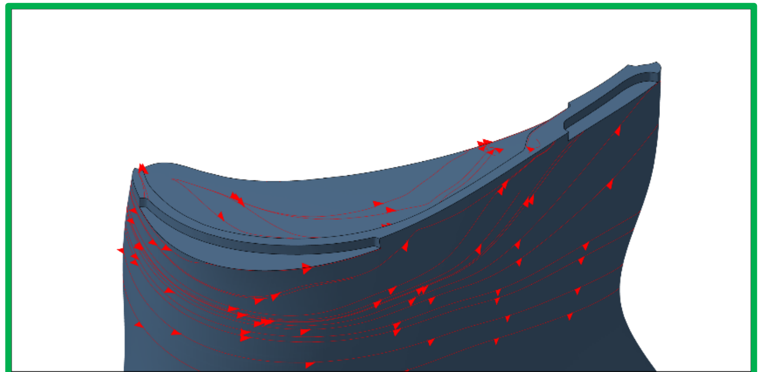
- Efficiency gains ~1.2%
- Tip heat load reduction ~13%











Blade and Tip Optimization Strategy

1.) Stage 1 Blade Optimization
2.) Stage 1 Blade Squealer Tip Optimization
3.) Stage 1 Vane-Blade Platform Cavity Optimization

Optimizes Aero and Heat Transfer Design

Genetic Algorithm Optimizer

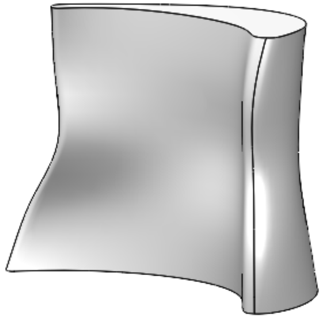
CENAERO
Fine/3D
CADO

Objective Function Evaluation

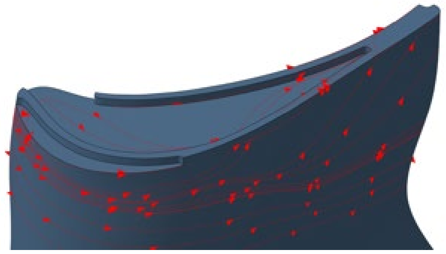
Parametrize Geometry → Design of Experiments → Creation of Individuals → Mesh Geometry → Solution (Numeca) → Post-Process

NIST sCO2 Tables

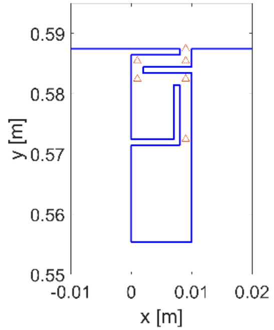
1.



2.



3.

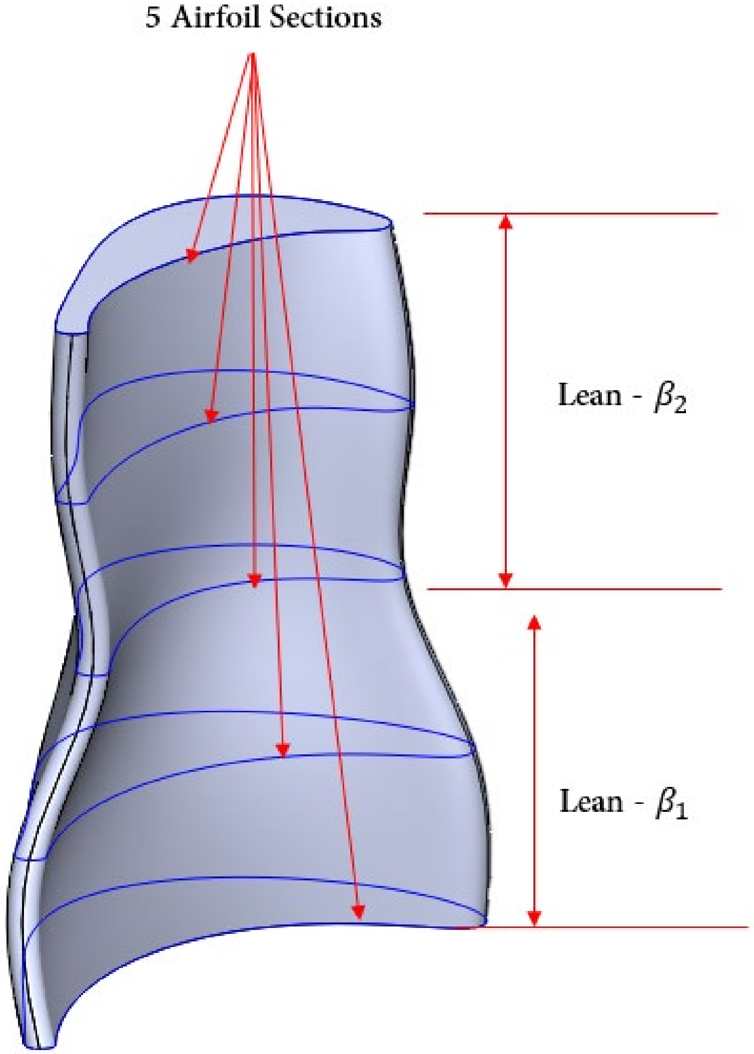


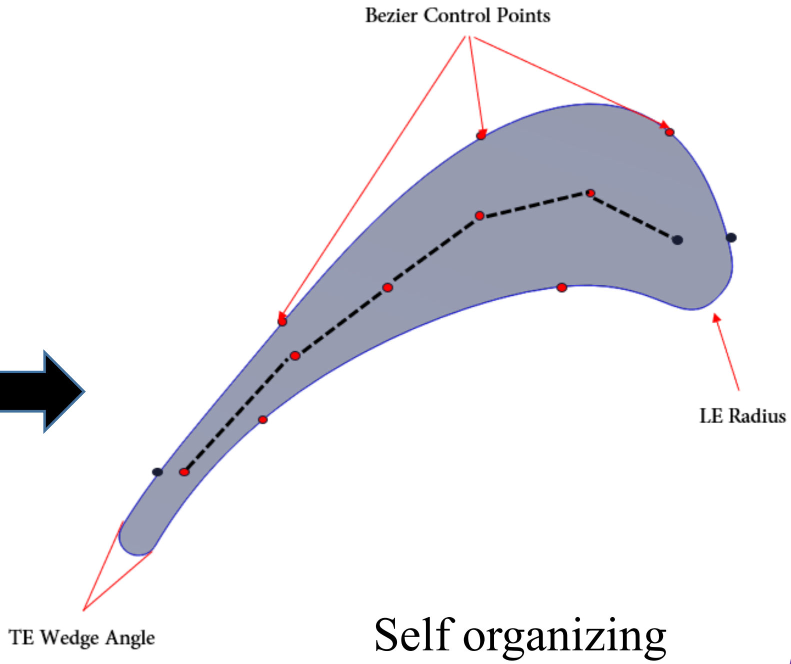
Subtask 2.2.2: Update Blade Design

Blade Parametrization

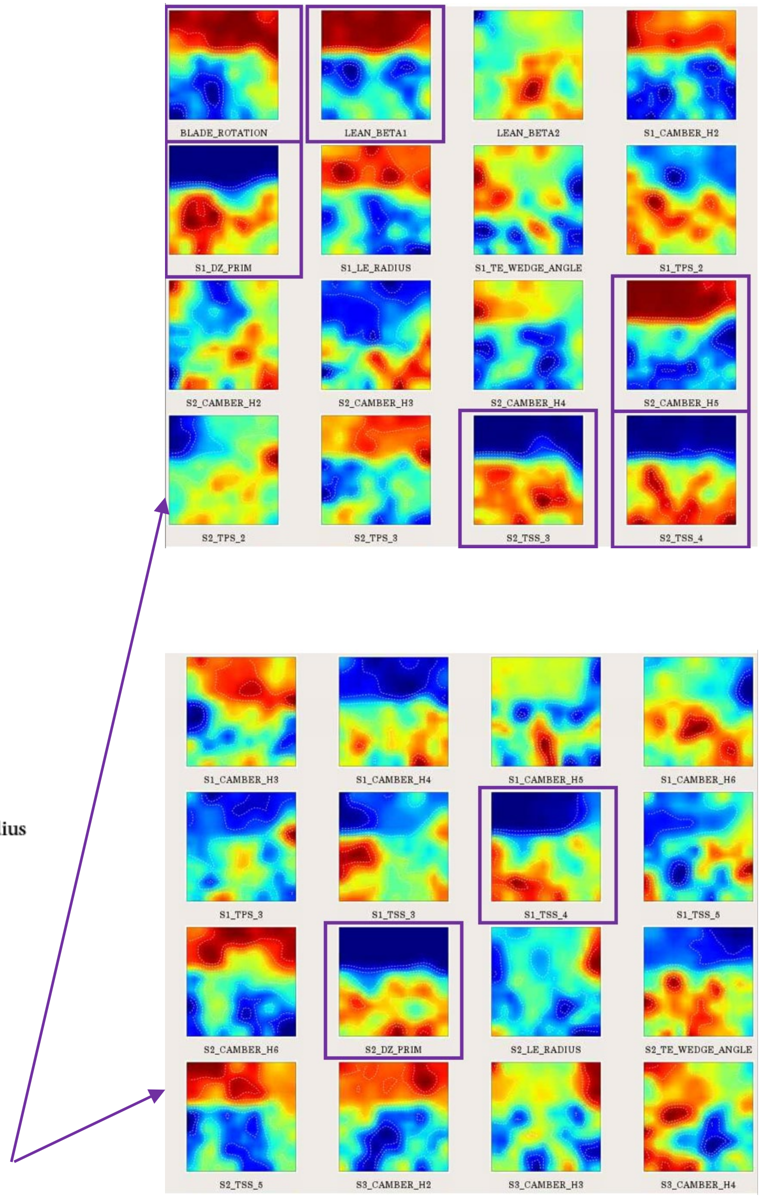
Full blade - 70 parameters

- 12 per airfoil section
- 5 sections
- 5 full blade parameters

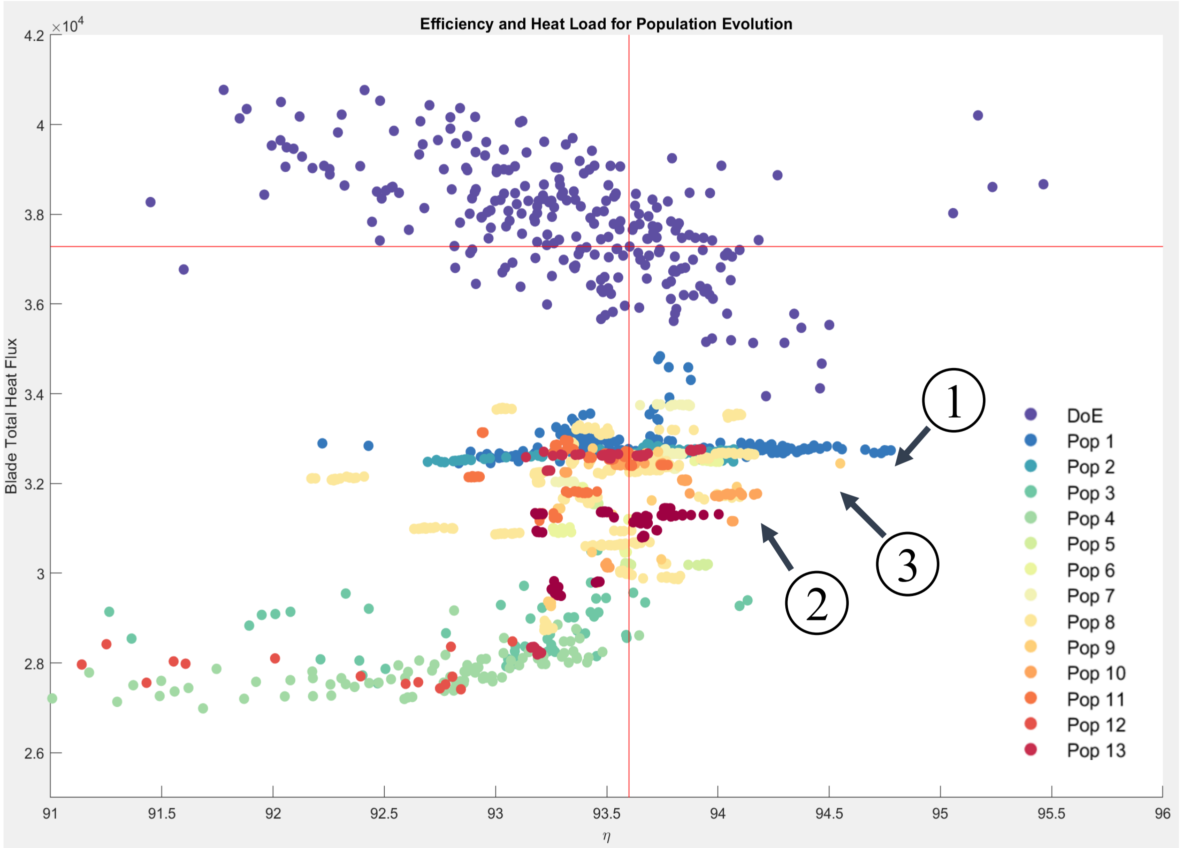




Self organizing maps identify key parameters affecting design -> focus further population creation



Blade Optimization



	INDIVIDUAL	% change η	% Change Heat Flux
1	497	+0.865	-12.104
2	1383	+0.545	-14.800
3	1794	+0.598	-12.431

3000 blade design iterations

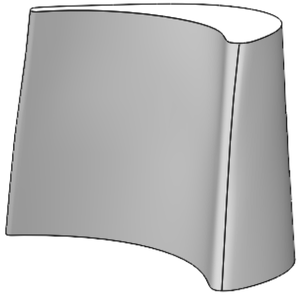
Objectives:

1.) Maximize isothermal corrected efficiency

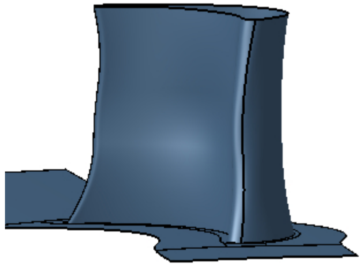
2.) Minimize heat load ($\dot{Q}$)

$$\rightarrow \eta_{iso_{corr}} = \frac{T_q\omega + \dot{Q}_{rotor} - T_{03}\left[\frac{\dot{Q}_{rotor}}{\frac{1}{2}(T_{02}+T_{03})}\right]}{\dot{m}\left[h_{01} - h_{03,is}\right]}$$

Constraint on mass flow to stay near cycle design



Baseline



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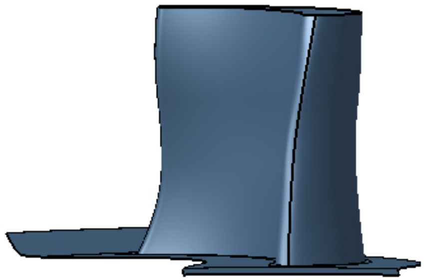
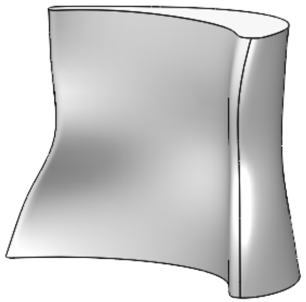


1



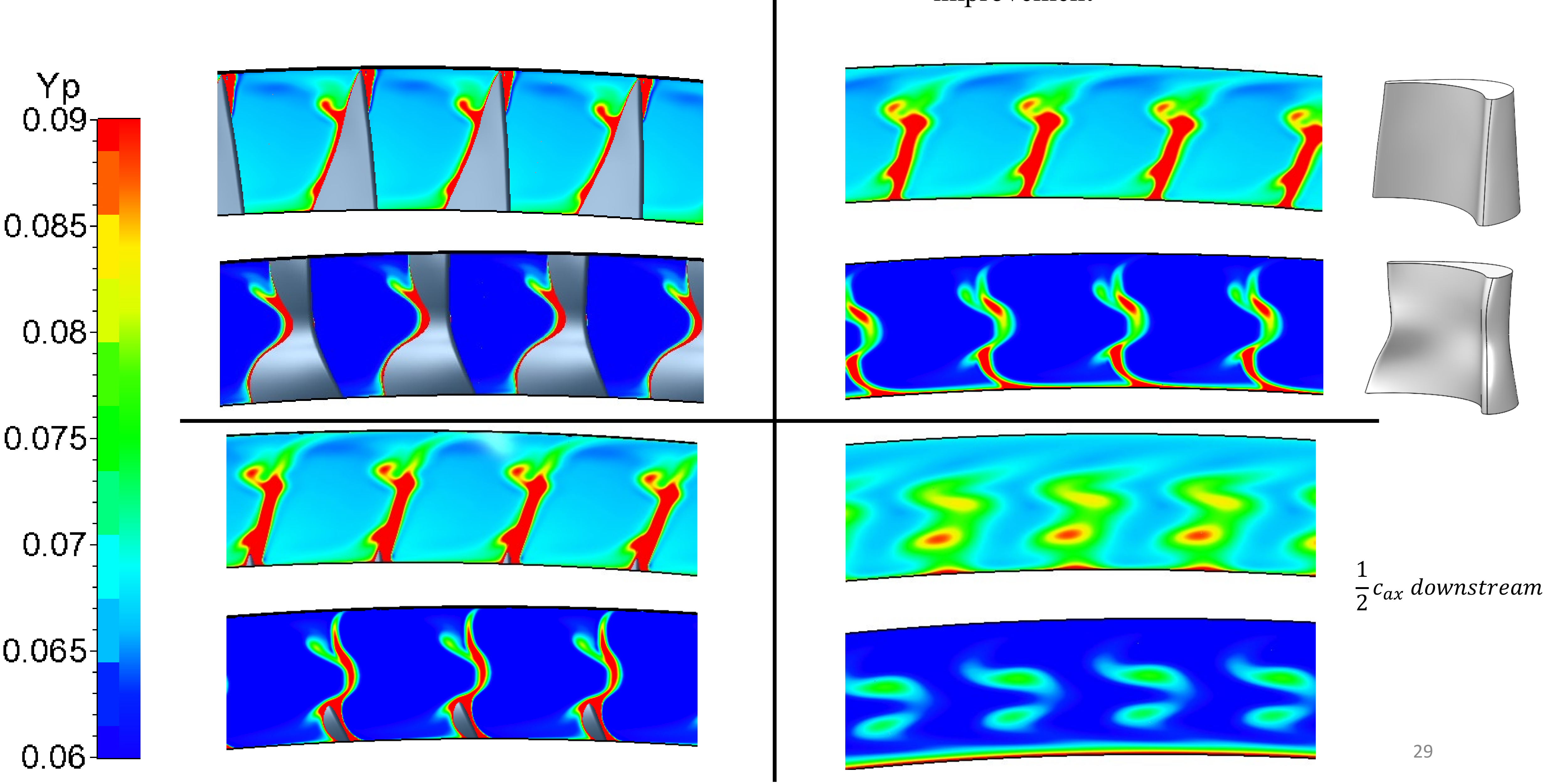
3

Designs chosen on manufacturability, modal analysis, and space for internal cooling

Blade Optimization

$$Y_p = \frac{P_{0,in} - P_{0,out}}{P_{s,measure} - P_{s,out}}$$

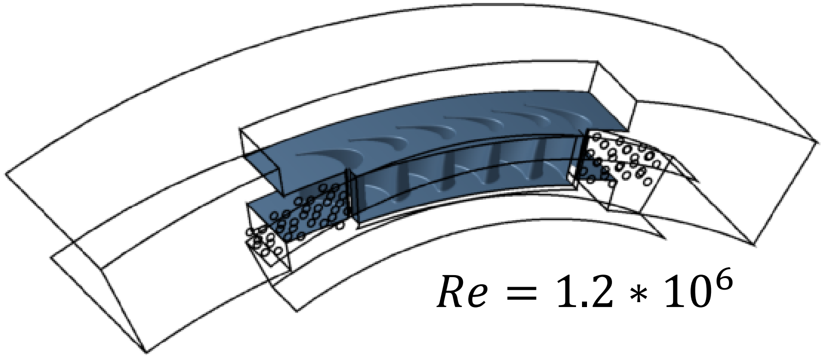
Separated loss cores in optimized design lead to loss improvement

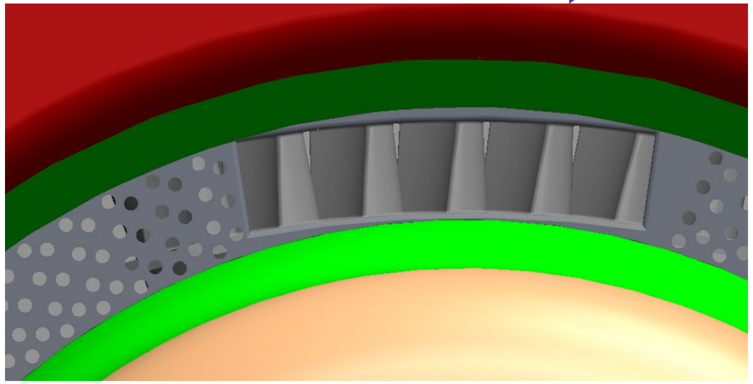


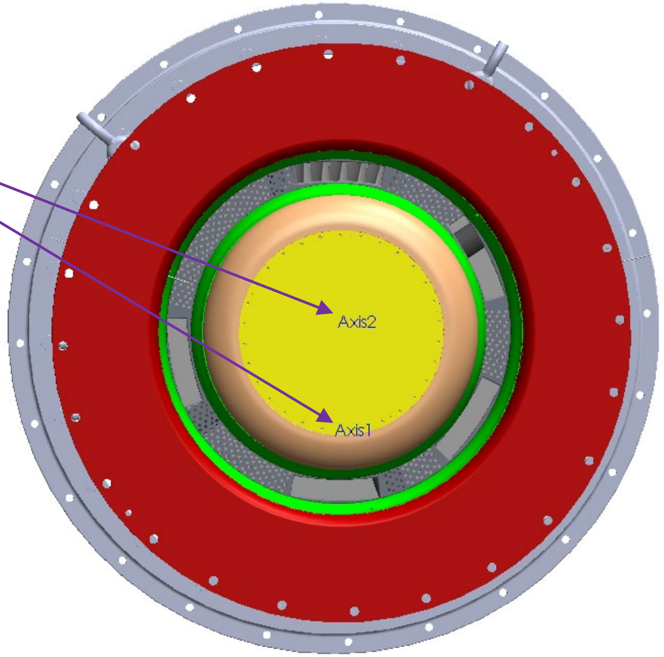
Subtask 2.2.3: Scaled Up Test Blade Design

Experimental Testing - BRASTA

Off-Axis Scaled design

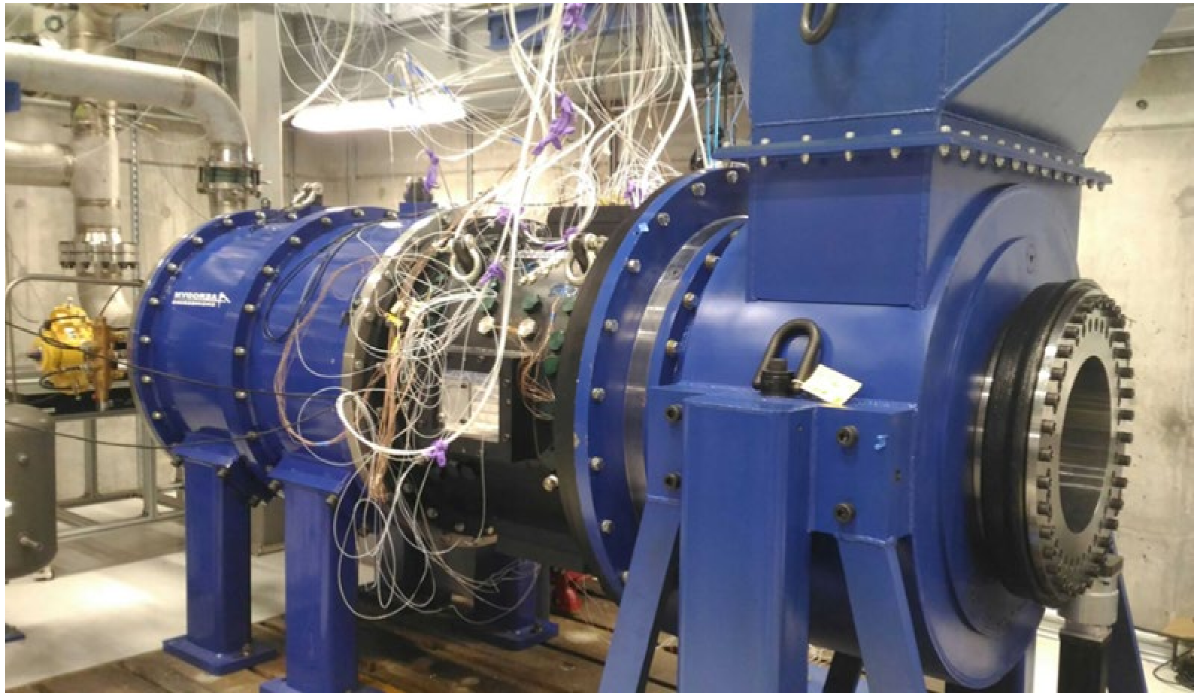




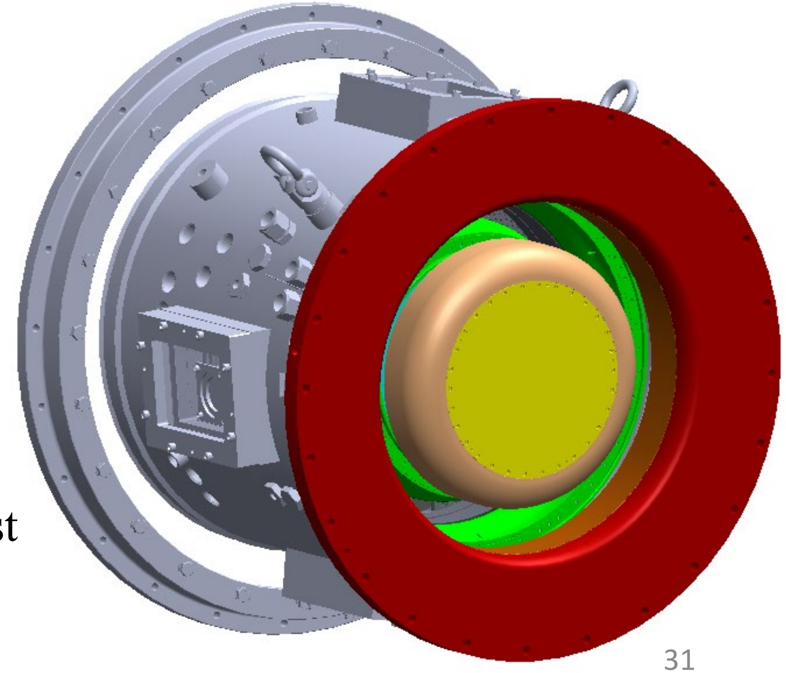


$Re = 1.2 * 10^6$

Scaling allows high Reynolds number testing indicative of demonstrator design

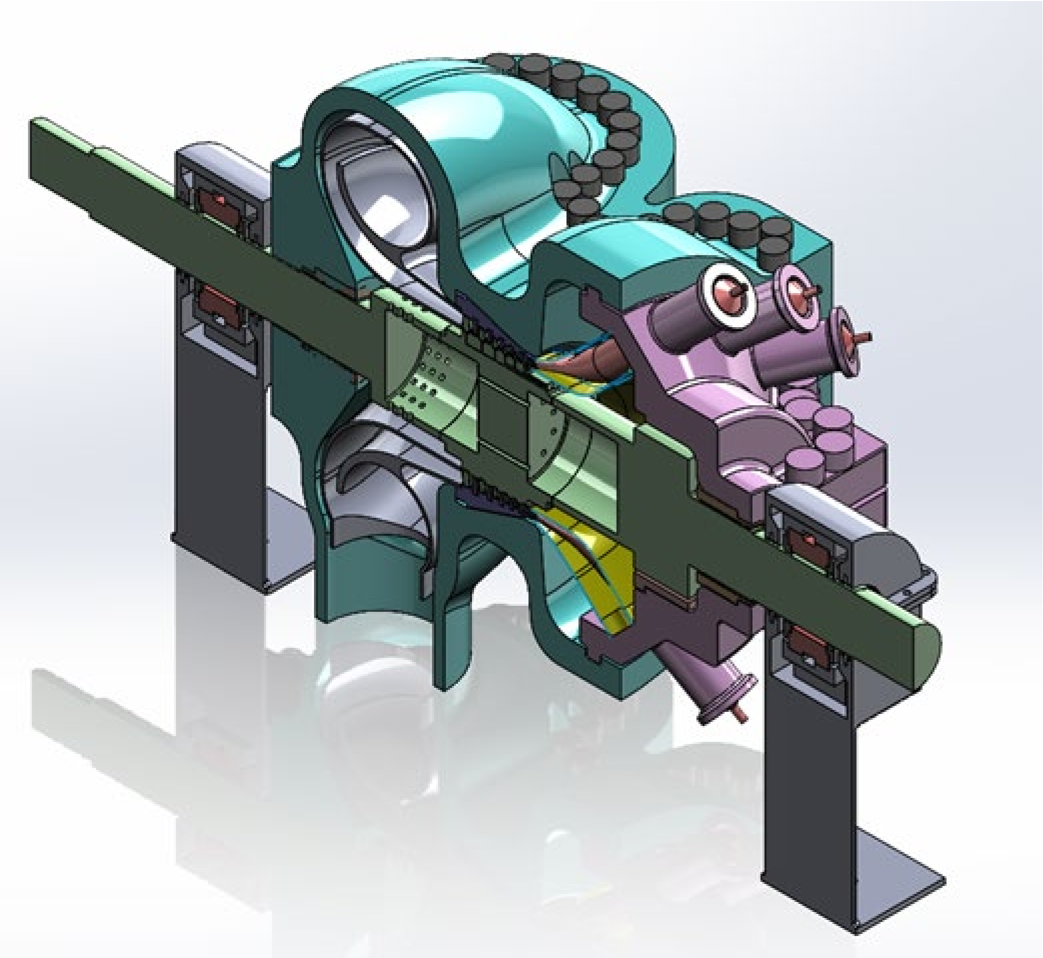


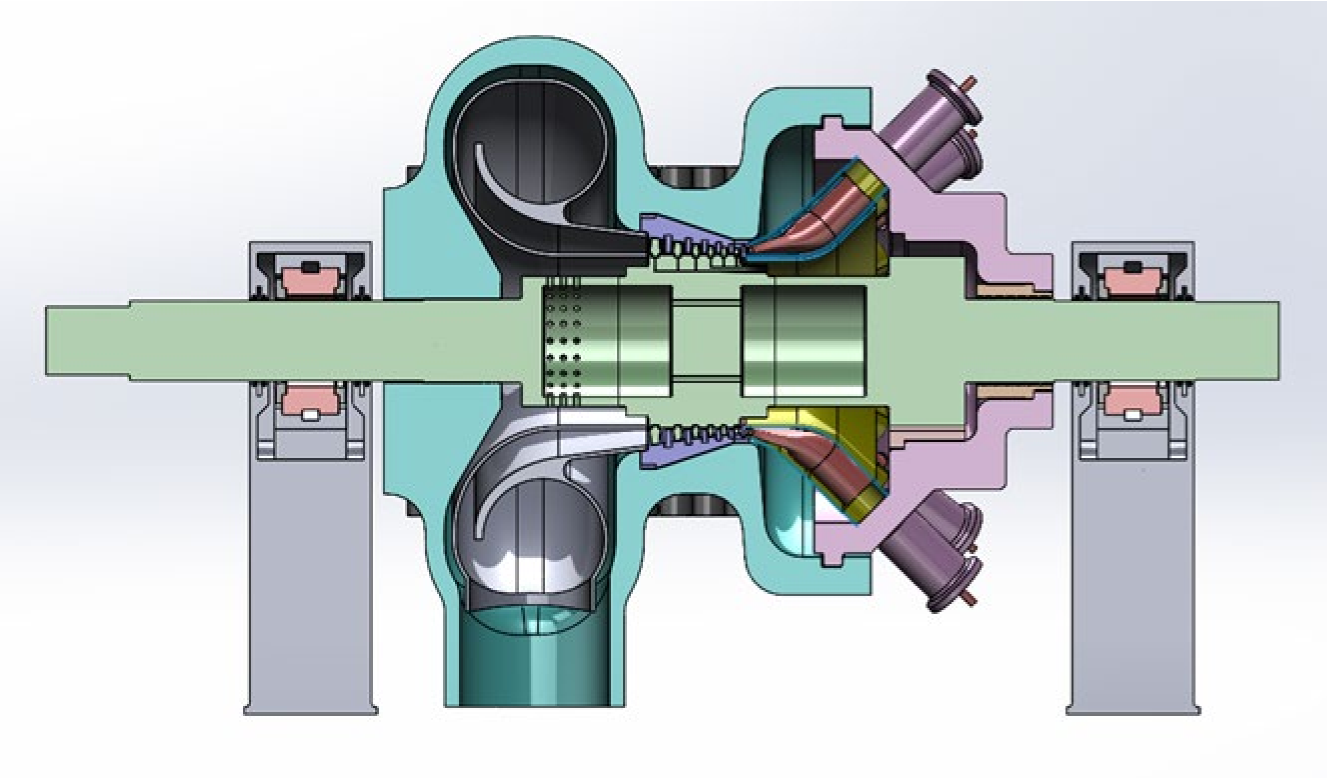
Sector design allows multiple airfoils in each test



BRASTA Annular Test Section
840 mm tip diameter

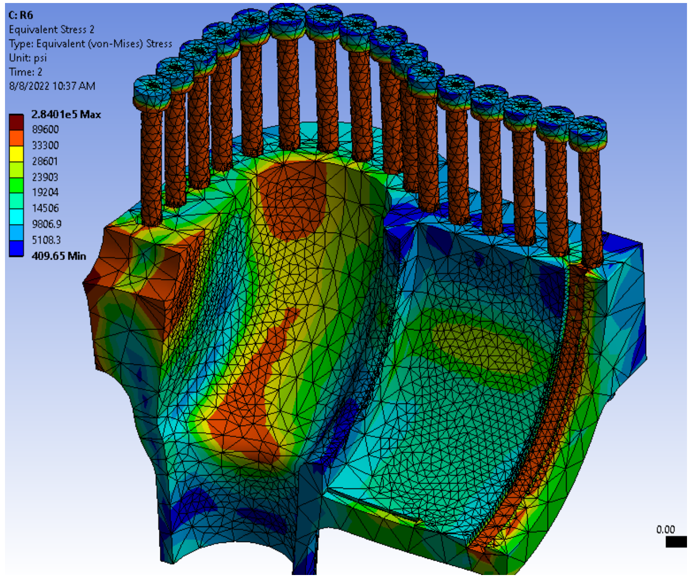
Subtask 2.2.5: Preliminary Case and Rotor Layout - SwRI

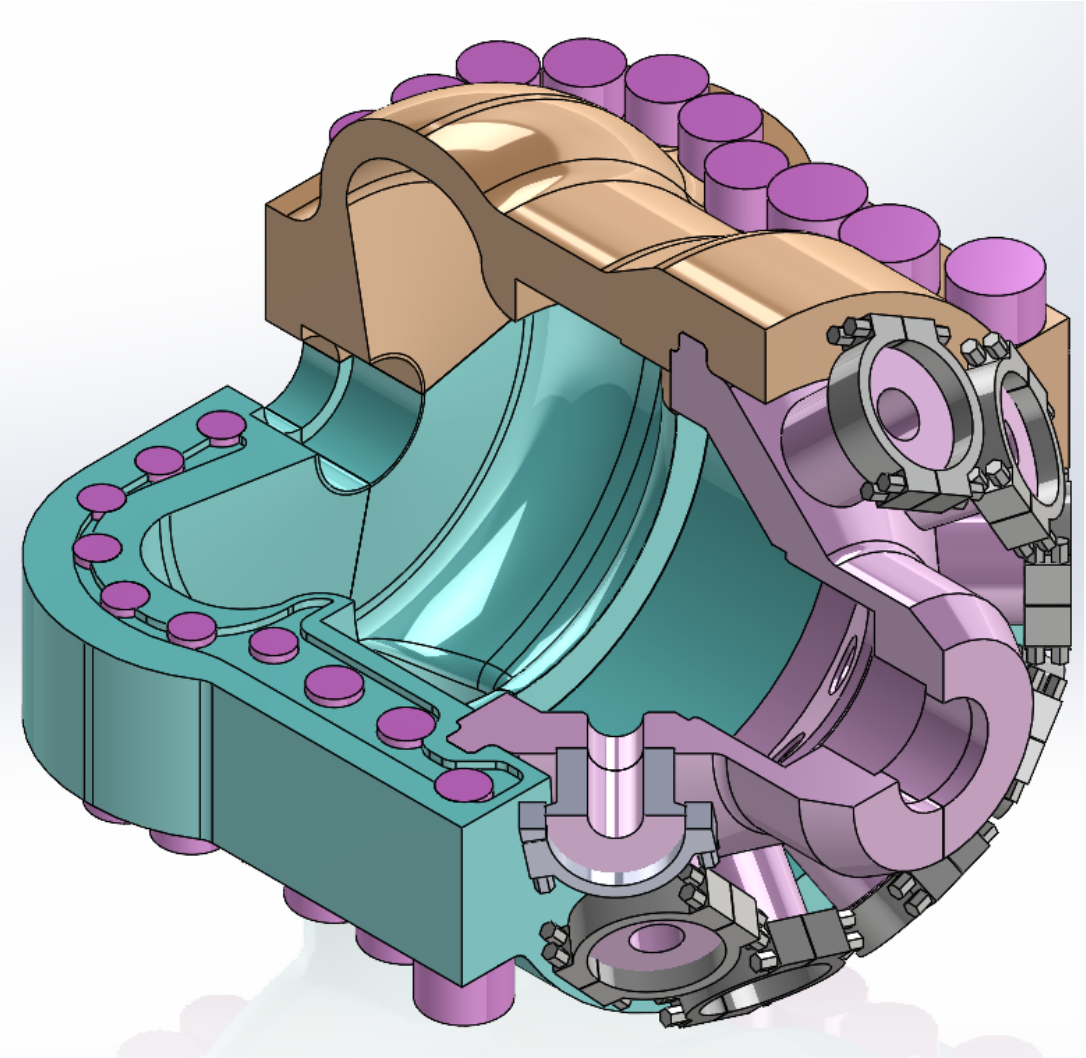




External Case Design

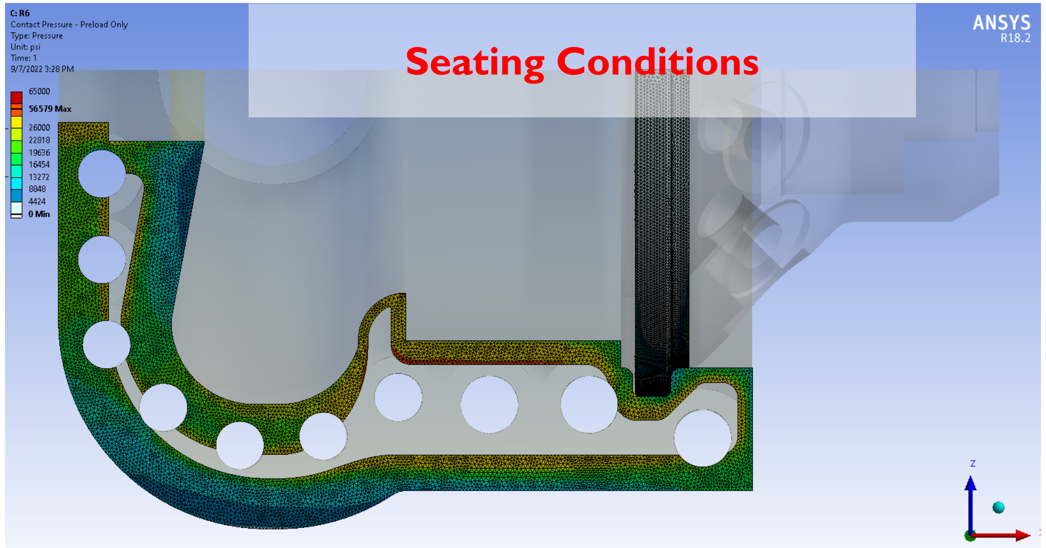
- Preliminary structural analysis
  - Linear, elastic-only analysis
  - ASME Boiler Pressure Vessel Code used to size pressure containment features

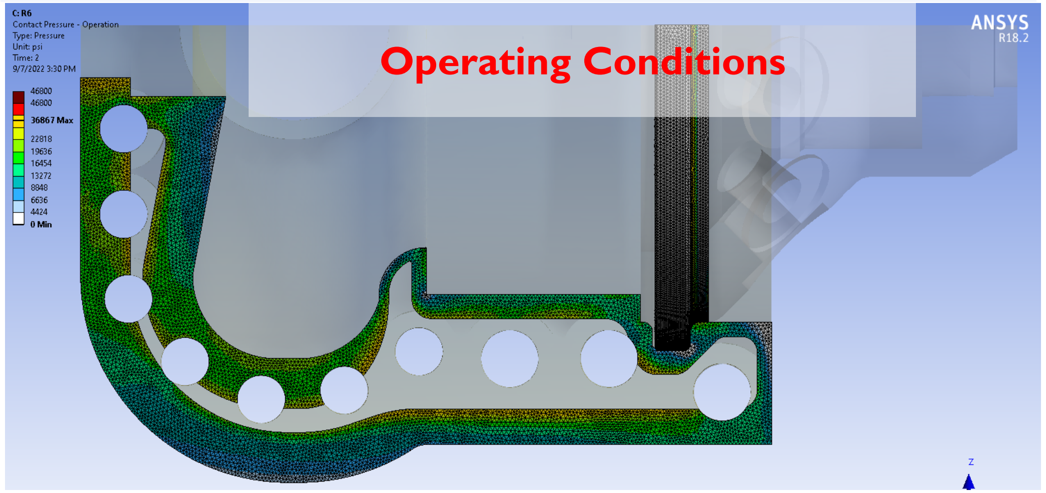




External Case Design

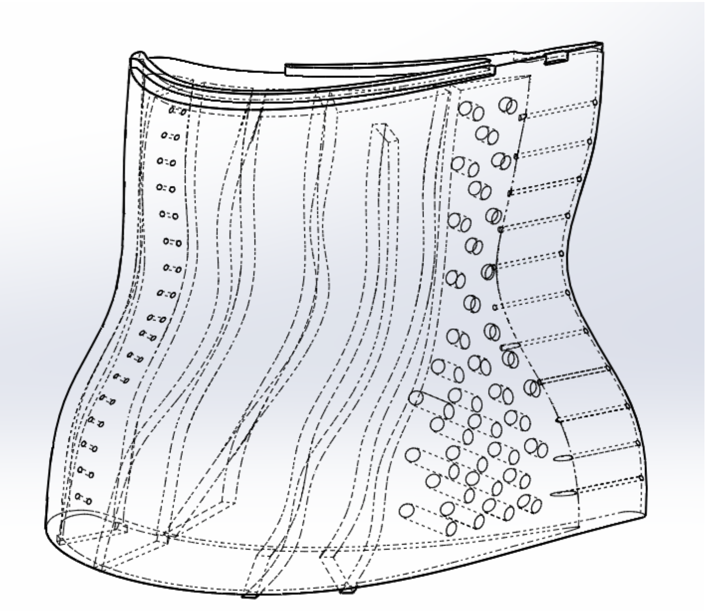
- Horizontal joint design
  - Flange sizing
  - Bolt configuration
  - Bolt Preload
  - Joint Stiffness
  - Sealing criteria
  - Sealing pressure
  - Thermal growth





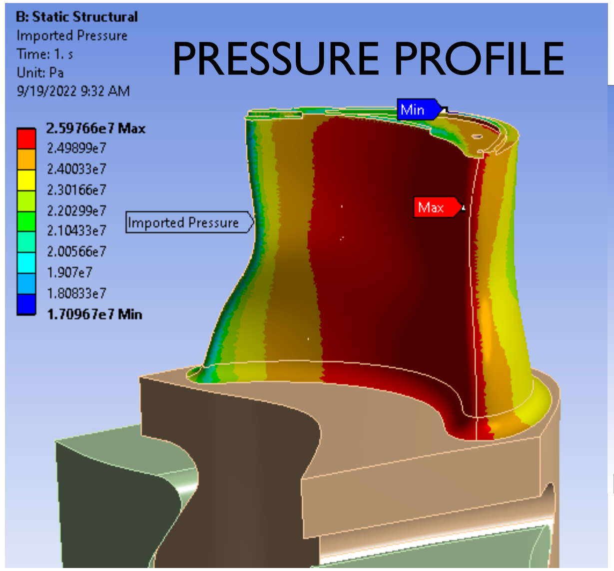
Blade Cooling

- Preliminary modeling of internal features
  - Serpentine channels
  - Leading edge impingement
  - Trailing edge pin-fin array

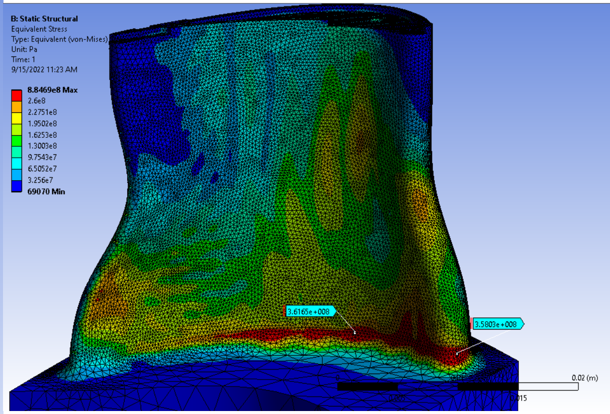


- Preliminary static structural analysis
  - Linear elastic, single body temperature
  - Surface pressure profile from CFD

- Next will update geometry
  - For structural improvement
  - Cooling features based on 1D heat transfer



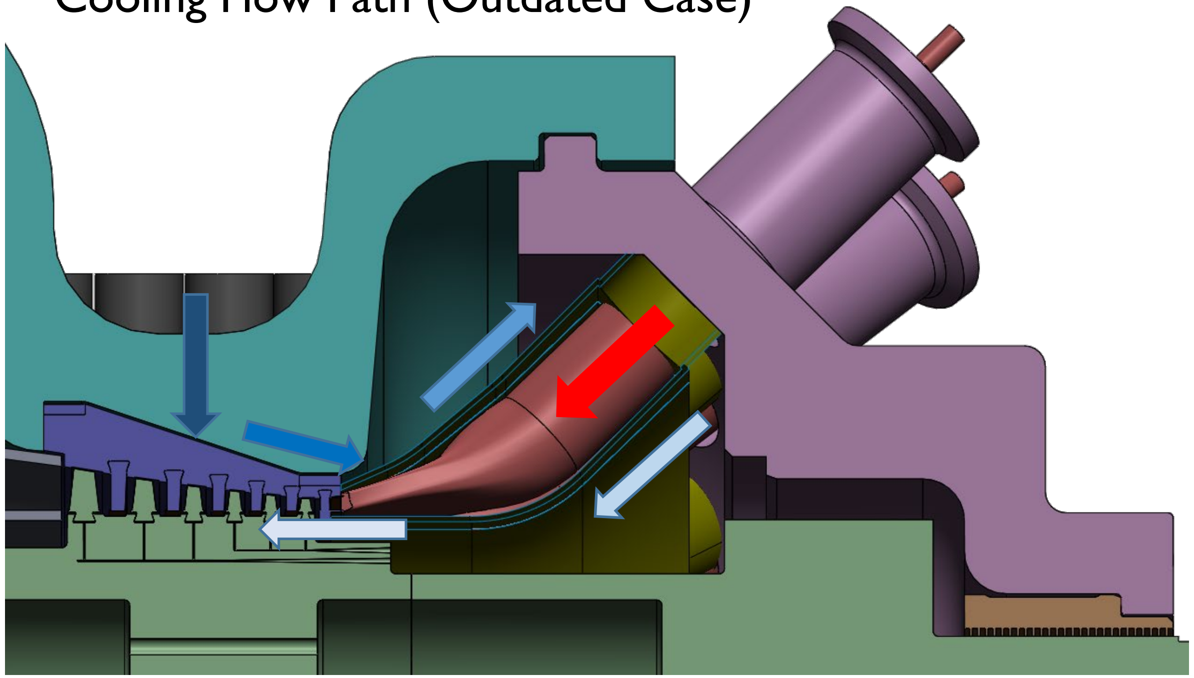
PRELIM STRESS RESULTS



Case Thermal Management

- Evaluating original cooling budget
- Current concept has single cooling stream servicing:
  - Stators
  - Combustor transition duct
  - Balance piston
  - Rotors
- Simple 1D model used to assess T and P of cooling flow along path
  - Marginal temperature increase and pressure drop found

Cooling Flow Path (Outdated Case)



Combustion RANS Simulation Conditions – Air Liquide

- Conditions of “Case-3A” (2021) of syngas combustion are used for the current simulation as summarized in the table below:

	Flow Rate (kg/h) (per can)	Temperature (°C)	Compositions (%)						
			CH4	O2	AR	CO	H2	CO2	H2O
Fuel	15943	89.3				38.	42.	20.	
Oxidant (60° Swirl)	57589	706.0		23.18	0.38			76.38	0.05
Recycle	177144	706.1		0.64	0.35			98.95	0.06

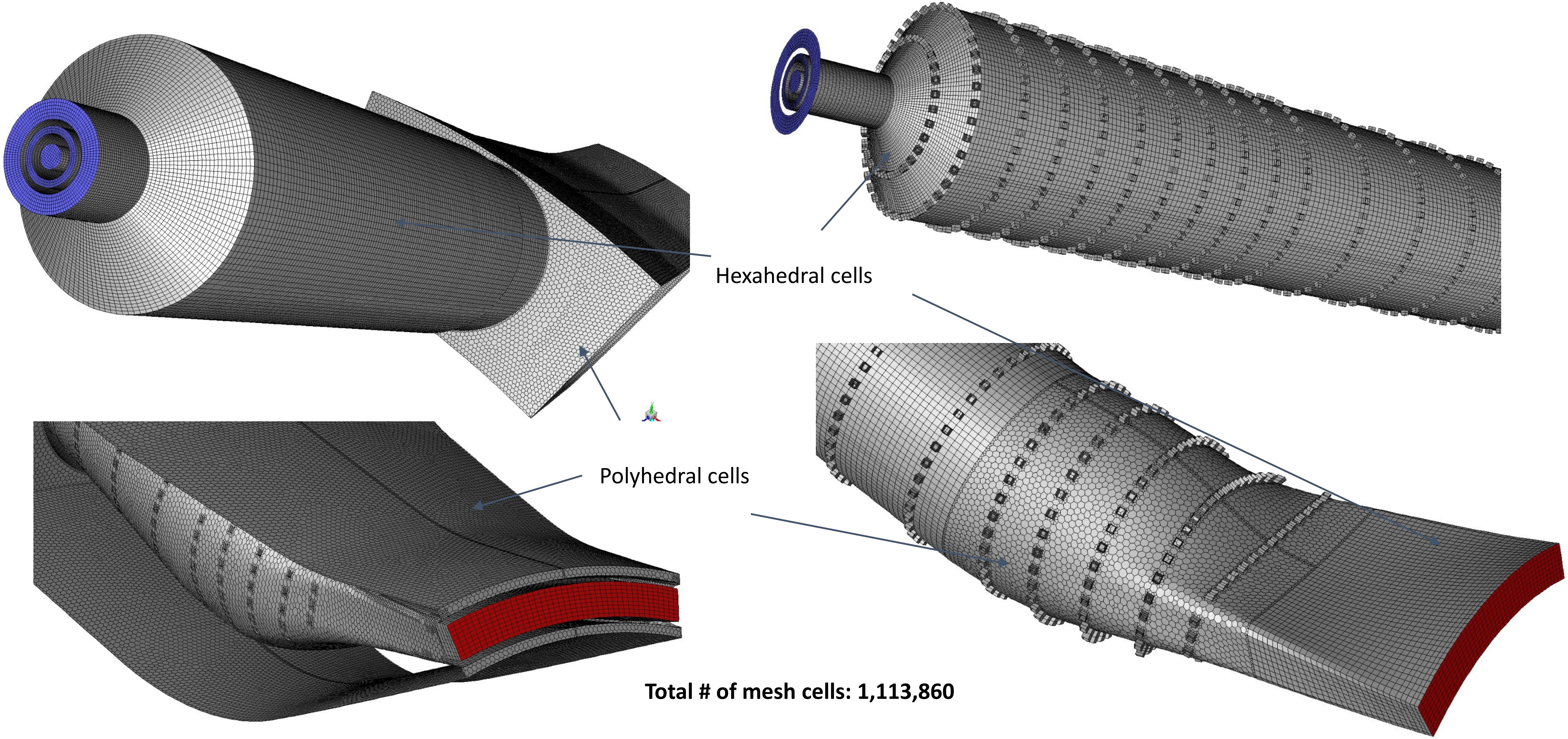
Reaction Mechanism

14 Species, 30 Reactions

no.	reaction	rate parameters[a] $A^{(b)}$	n	E	f^c	ref/ comments[c]
1	$H+O_2=O+OH$	2.65(16)	−0.671	17041	1.15	[8]
2	$O+H_2=H+OH$	3.87(04)	2.7	6260	1.3	[8]
3	$OH+H_2=H+H_2O$	2.16(08)	1.51	3430	1.3	[8]
4	$2OH=O+H_2O$	3.57(04)	2.4	−2110	1.3	[8]
5	$2H+M=H_2+M$	1.00(18)	−1		2	[8]
5a	$H_2O/60T^{-0.25}/$				2	*d*
	$H_2/0.0506T^{0.4}/$, CO/1/, $CO_2/309T^{-1}/$, Ar/0.63/, He/0.63/					
6	$H+OH+M=H_2O+M$	2.20(22)	−2		2	[8]
	$H_2/2/$, $H_2O/6.3/$, CO/1.75/, $CO_2/3.6/$, Ar/0.38/, He/0.38/					
7	$O+H+M=OH+M$	4.71(18)	−1		2	[9]
	$H_2/2/$, $H_2O/12/$, CO/1.75/, $CO_2/3.6/$, Ar/0.7/, He/0.7/					
8	$2O+M=O_2+M$	1.20(17)	−1			[8]
	$H_2/2.4/$, $H_2O/15.4/$, CO/1.75/, $CO_2/3.6/$, Ar/0.83/, He/0.83/					
9	$H+O_2(+M)=HO_2(+M)$	4.65(12)	0.44		1.2	[2], k_∞
		5.75(19)	−1.4		1.2	k_0, *e*
9a	Ar/0.53/				1.2	*d*
9b	He/0.53/				1.2	*d*
9c	$O_2/0.75/$				1.2	*d*
9d	$H_2O/12/$				1.2	*d*
9e	$H_2/1.0/$				1.2	*d*
	CO/1.2/, $CO_2/2.4/$					
10	$H_2+O_2=HO_2+H$	7.40(05)	2.433	53502	1.25	[10]
11	$2OH(+M)=H_2O_2(+M)$	7.40(13)	−0.37		1.5	[11], k_∞
		1.34(17)	−0.584	−2293	1.5	k_0, *f*
	$H_2/2/$, $H_2O/6/$, CO/1.75/, $CO_2/3.6/$, Ar/0.7/, He/0.7/					
12	$HO_2+H=O+H_2O$	3.97(12)		671		[8]
13	$HO_2+H=OH+OH$	7.08(13)		295	2	[13]
14	$HO_2+O=OH+O_2$	2.00(13)			2	[8]
15a	$HO_2+OH=O_2+H_2O$	2.90(13)		−500	2	[14]
15b		1.00(16)		17330		[15]
16a	$2HO_2=O_2+H_2O_2$	1.30(11)		−1630		[16]
16b		4.20(14)		12000	1.5	[16]
17	$H_2O_2+H=HO_2+H_2$	1.21(07)		25200	2	[8]
18	$H_2O_2+H=OH+H_2O$	2.41(13)		3970		[9]
19	$H_2O_2+O=OH+HO_2$	9.63(06)		23970		[9]
20a	$H_2O_2+OH=HO_2+H_2O$	2.00(12)		427		[15]
20b		2.67(41)		−737600		*g*
21	$CO+O(+M)=CO_2(+M)$	1.80(10)		2384	2	[13], k_∞
		1.55(24)	−2.79	4191	2	k_0, *h*
	$H_2/2/$, $H_2O/12/$, CO/1.75/, $CO_2/3.6/$, Ar/0.7/, He/0.7/					
22a	$CO+OH=CO_2+H$	9.60(11)	0.14	7352	1.2	*i*
22b		7.32(10)	0.03	−16	1.2	*i*
23	$CO+O_2=CO_2+O$	2.53(12)		47700	3	[9]
24	$CO+HO_2=CO_2+OH$	3.01(13)		23000	2	[1]
25	$HCO+H=CO+H_2$	1.20(14)			2	[17]
26	$HCO+O=CO+OH$	3.00(13)				[8]
27	$HCO+O=CO_2+H$	3.00(13)				[8]
28	$HCO+OH=CO+H_2O$	3.02(13)				[9]
29	$HCO+M=CO+H+M$	9.35(16)	−1	17000	2	[17]
29a	$H_2O/12/$				2	*d*
	$H_2/2/$, CO/1.75/, $CO_2/3.6/$, Ar/1/, He/1/					
30	$HCO+O_2=CO+HO_2$	1.20(10)	0.807	−727		[18]

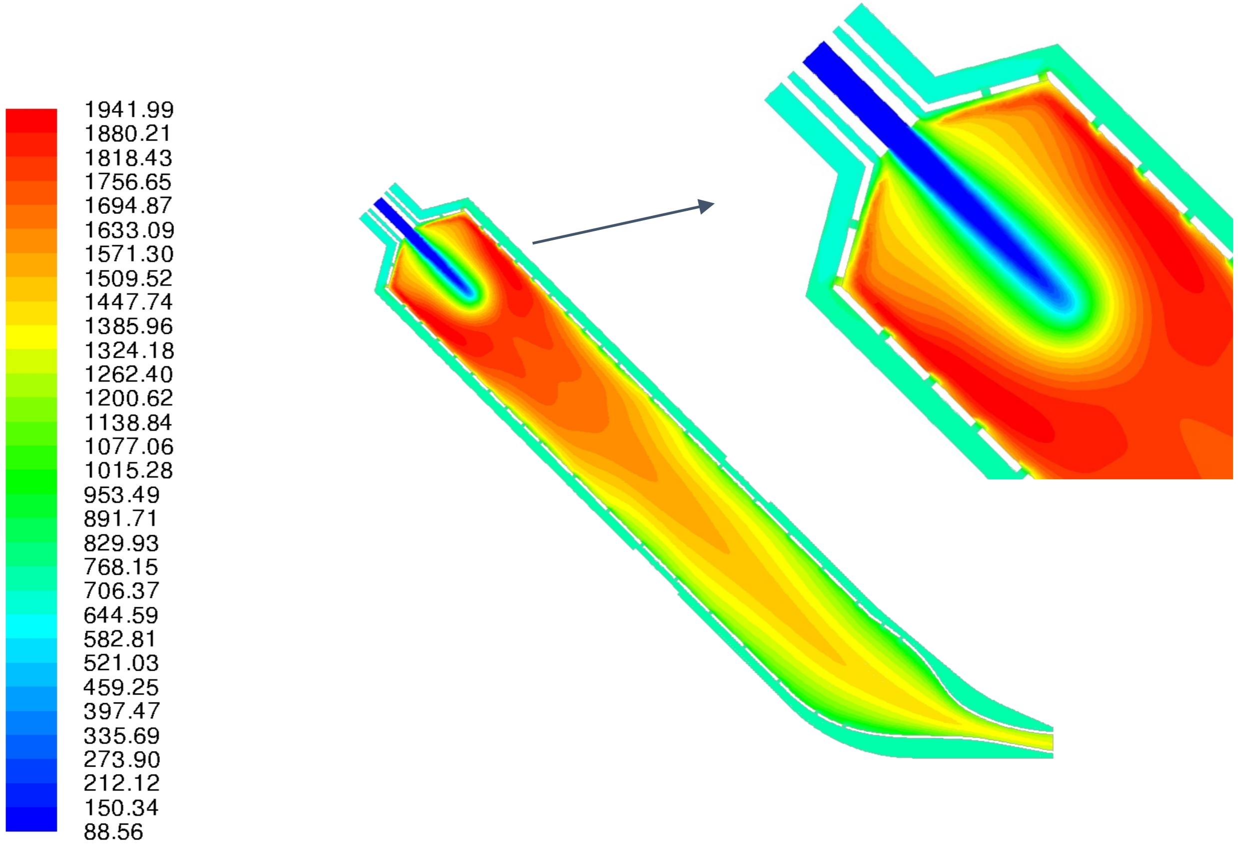
[a] Rate parameters $k=AT^n\exp(-E/RT)$. Units are cm, s, mol, and cal. Unless otherwise indicated, multiple entries of rate expressions for a reaction indicate the rate coefficient is the sum of these expressions. [b] The number in the parenthesis is the exponent of 10, i.e., 2.65(16) = 2.65×10^{16}. Parameters highlighted in red are active and subject to optimization. [c] f is the uncertainty factor or span assigned to active A factors. [d] The third-body collision efficiency is active and subject to optimization. [e] Center broadening factor $F_c = 0.5$. [f] Low-pressure limit fit to expressions given in [11] and [12]. $F_c = 0.2654\exp(-T/1756) + 0.7346\exp(-T/5182)$. [g] Fit to the expression of [16]. [h] $F_c = 1$ (Lindemann fall-off). [i] This work (see text).

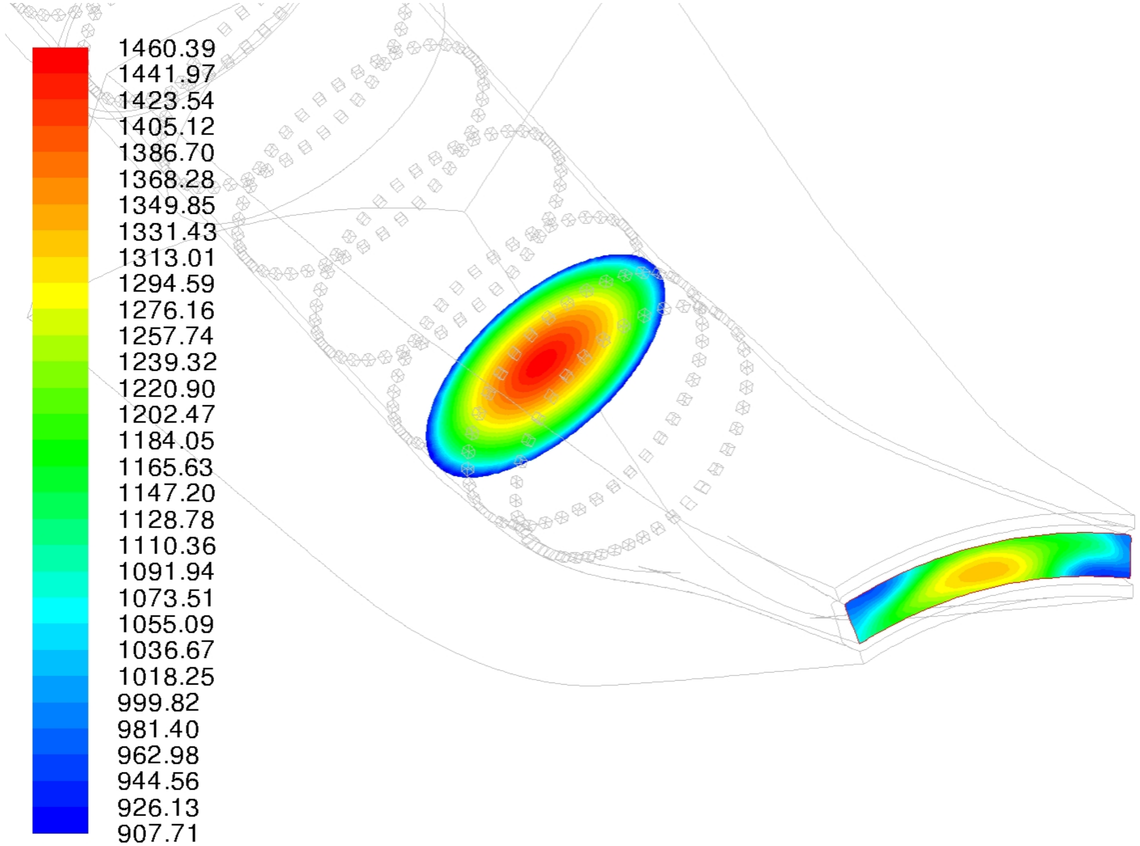
Simulation Model and Mesh



Total # of mesh cells: 1,113,860

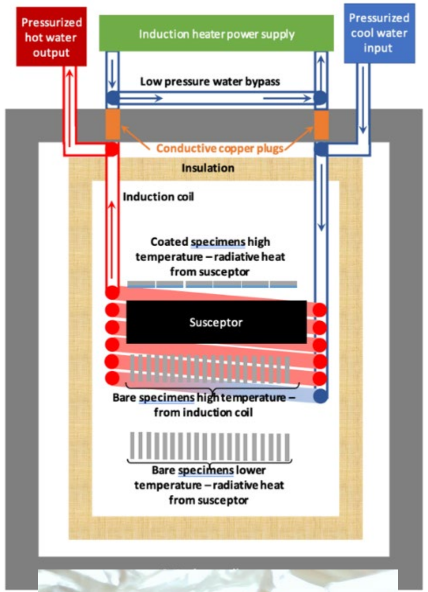
Simulation Results (Case #4)





Temperature (°C) profiles

Task 2.3 – Autoclave Material Testing

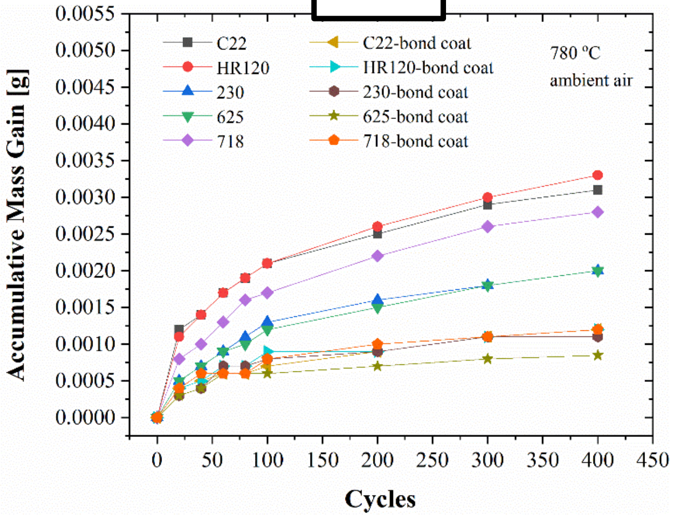


1150°C High-Temp Autoclave

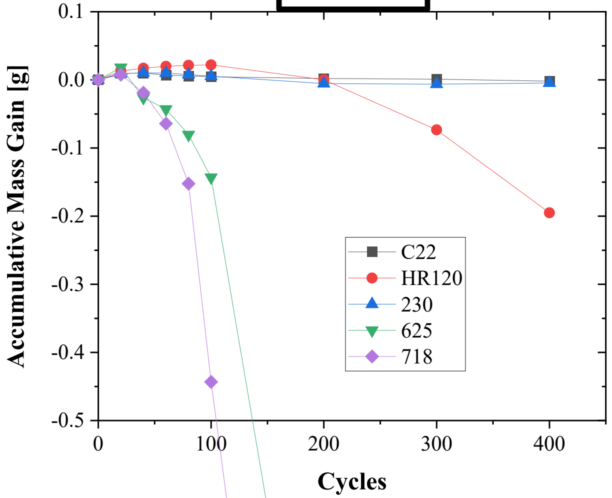
<u>Material Testing</u>

- Thermal Cycling at ambient air at 780°C.
    - All uncoated materials showed significant oxidation, degradation, and mass gain
    - Bond coated with MCrAlY/TiN using plasma enhanced magnetron sputtering (PEMS) showed only discoloration on the surface.
    - Bond coating provided good protection of the base materials in air up to 780°C.
- At 1050°C all uncoated alloys exhibited a slight mass gain in the first 50 cycles due to surface oxidation.
    - A few materials such as 625 and 718 showed a mass loss after 50 cycles.
    - Coated samples exhibited improved thermal cycling at 1050°C with only 718 bond coated showing a mass loss.
- Samples for Induction heating autoclave testing at 1150°C and 5,000 psi CO_2 have been machined.
    - Samples are currently being bond coated and TBC coated for long term high pressure high temperature testing.
- 1150C, 300 bar autoclave being commissioned

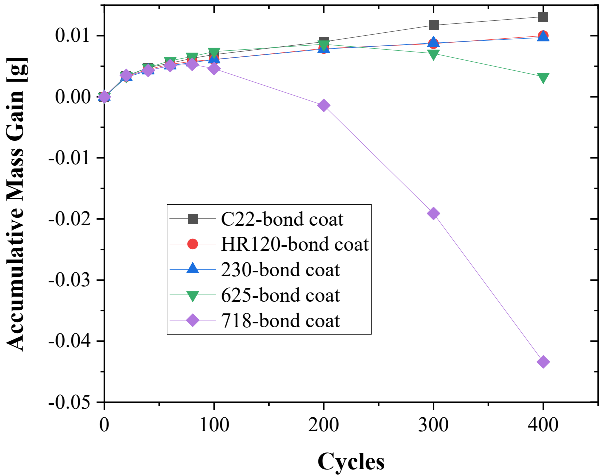
780°C



1050°C



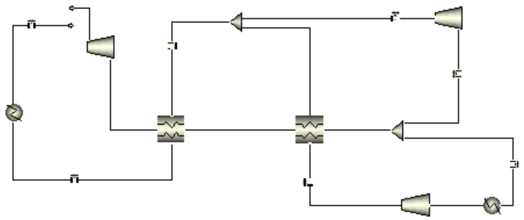
1050°C



Task 2.4 – Updated Syngas Combustion Cycle: Evaluate Retrofit of STEP Facility for Oxy-Fuel Turbine Testing – 8 Rivers

Efforts to date:

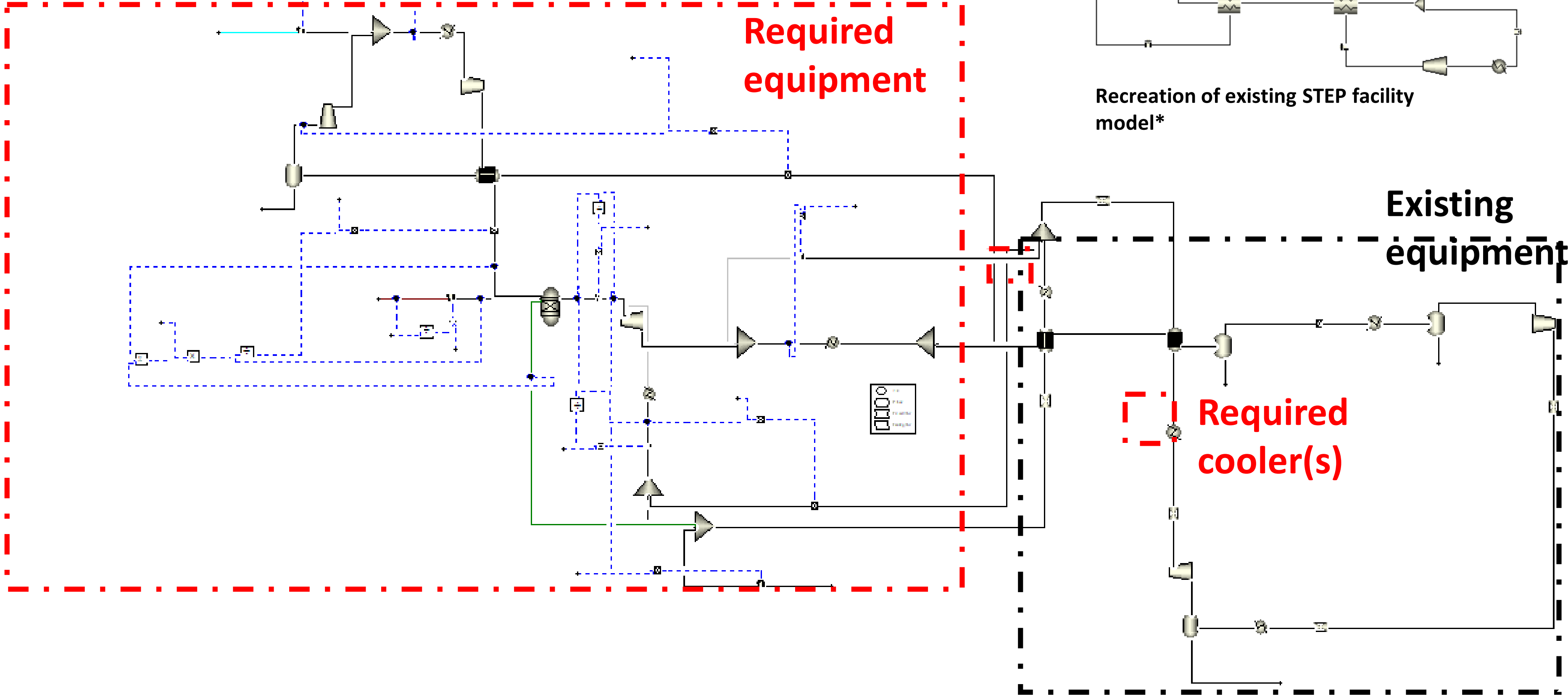
- Basic STEP facility model recreated to provide the foundation for modifications towards a high-temperature, direct-fired model
- Low-temperature (715 °C), direct-fired model completed without major modification to existing facility setup
- High-temperature (1150 °C TIT) case being actively explored using dynamic simulations
    - Results have thus far been positive, suggesting that the STEP facility can indeed support the testing of a high-temperature, direct-fired turbine
    - Once complete, the design will be imported back into a static model for HMB generation and equipment costing



Recreation of existing STEP facility model*

Upcoming work:

- Exploring limit conditions regarding existing equipment (compressor head, recuperator volume flow, etc.) to determine final feasible arrangements
- Costing all necessary equipment for the high-temperature case
- Optimizing the cycle & shortlisting options to discuss with the STEP team



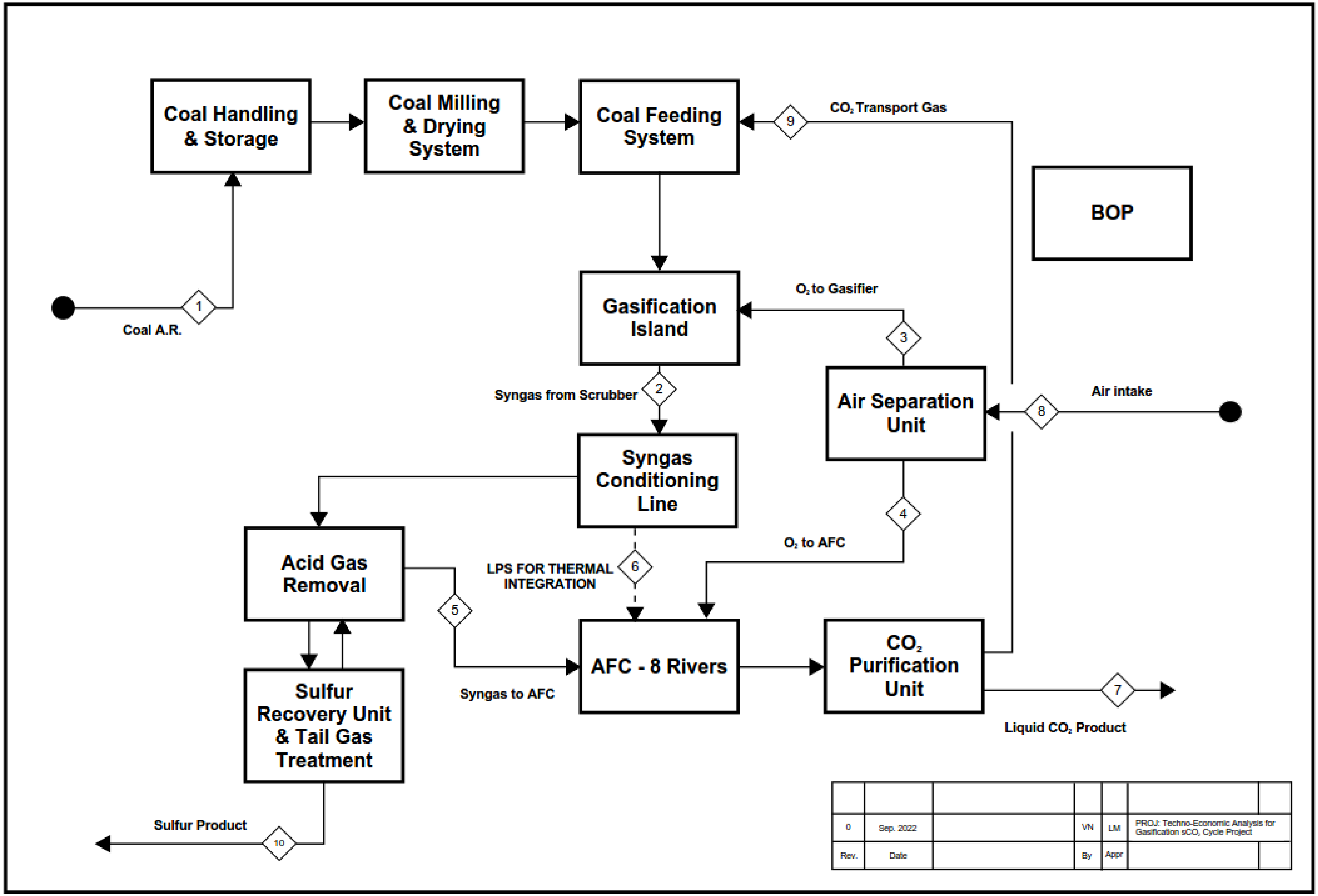
Task 2.5 – Initial Techno-Economic Assessment – EPRI/Wood

- The US DOE is funding a project to develop a syngas oxy-combustion turbine for supercritical carbon dioxide (sCO2) cycle power plants
- Southwest Research Institute (SwRI) is the prime contractor, while EPRI and 8-Rivers are subcontractors to SwRI
- As a subcontractor to EPRI, Wood is performing a techno-economic assessment (TEA) of a direct syngas-fired sCO2 power cycle incorporating the new sCO2 turbine
- The main objectives of this TEA are:
  - Pre-screening of potential coal gasification technologies
  - Evaluation of a ~300 MWe sCO2 power plant case integrated with the recommended gasification technology

Task 2.5 – Initial Techno-Economic Assessment

- Coal: PRB subbituminous
- Reference plant site: standard Montana site used in DOE/NETL's low rank baseline studies
- Plant based on one power cycle, including:
  - One oxy-combustion direct-fired CO2 turbine
  - One main heat exchanger for recycled gas pre-heating
  - One recycled gas compression loop
- CO_2 capture: >98%
- The gasification screening task selected a generic dry-feed, entrained flow quench gasifier technology based on lower capital cost, feedstock flexibility, and ease of integration with the sCO2 power cycle

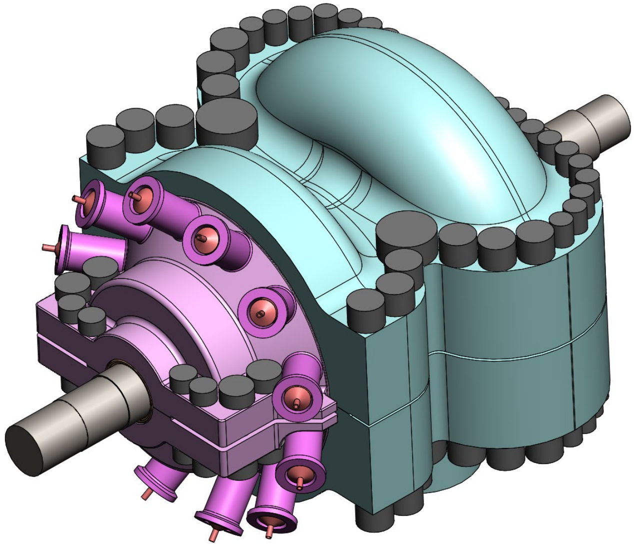
Overall Block Flow Diagram



Preliminary Performance Summary

Direct-fired sCO2 turbine power output	MWe	474.9
GROSS ELECTRIC POWER OUTPUT (D) (@ gen terminals)	**MWe**	**474.9**
8Rivers	MWe	89.0
Gasification and Syngas Conditioning	MWe	6.0
Air separation unit	MWe	82.0
CO2 purification and compression unit	MWe	4.9
Utility & Offsite Units	MWe	9.9
ELECTRIC POWER CONSUMPTION	**MWe**	**191.8**
NET ELECTRIC POWER OUTPUT	**MWe**	**283.1**
(Step Up transformer efficiency = 0.997%) (C)	MWe	282.3
Gross electrical efficiency (D/A x 100) (based on LHV)	**%**	**64.9%**
Net electrical efficiency (C/A x 100) (based on LHV)	**%**	**38.6%**
Gross electrical efficiency (D/A' x 100) (based on HHV)	**%**	**62.6%**
Net electrical efficiency (C/A' x 100) (based on HHV)	**%**	**37.2%**
Equivalent CO_2 flow in fuel	kmol/h	5723
Captured CO_2	kmol/h	5656
CO_2 removal efficiency	**%**	**98.8**
Fuel Consumption per net power production	**MWth/MWe**	**2.59**
CO_2 emission per net power production	**kg/MWh**	**1.8**

Summary



- ***Task 2.1 - Heat Transfer Testing***
  - Heat transfer correlations to high Reynolds number needed for SCO2
  - Internal heat transfer rig under construction
  - Impingement heat transfer in SCO2 complete
  - Pin-Fin heat transfer in SCO2 nearing completion
- ***Task 2.2 – Turbine Preliminary Design***
  - Turbine blade and tip have been optimized for aerodynamic performance and heat transfer
  - Aerodynamic cascade test hardware procured
  - Preliminary Case and Rotor Layout nearing completion including pressure containment, blade mechanical design, and cooling scheme
- ***Task 2.3 – Autoclave Material Testing***
  - Thermal Cyclic Testing at 780°C and 1050°C in Ambient Air complete
    - Bond coated samples performed well up to 1050°C
  - High Pressure/Temperature Material Autoclave being commissioned
- ***Task 2.4 – Updated Syngas Combustion Cycle***
  - STEP Facility retrofit to oxy-fuel turbine evaluated and shows to be feasible for retrofit
- ***Task 2.5 – Initial Techno-Economic Assessment***
  - Provided modeling of gasification system and power block demonstrating good performance with carbon capture

Questions?