DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

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

UTSR Project Review Meeting

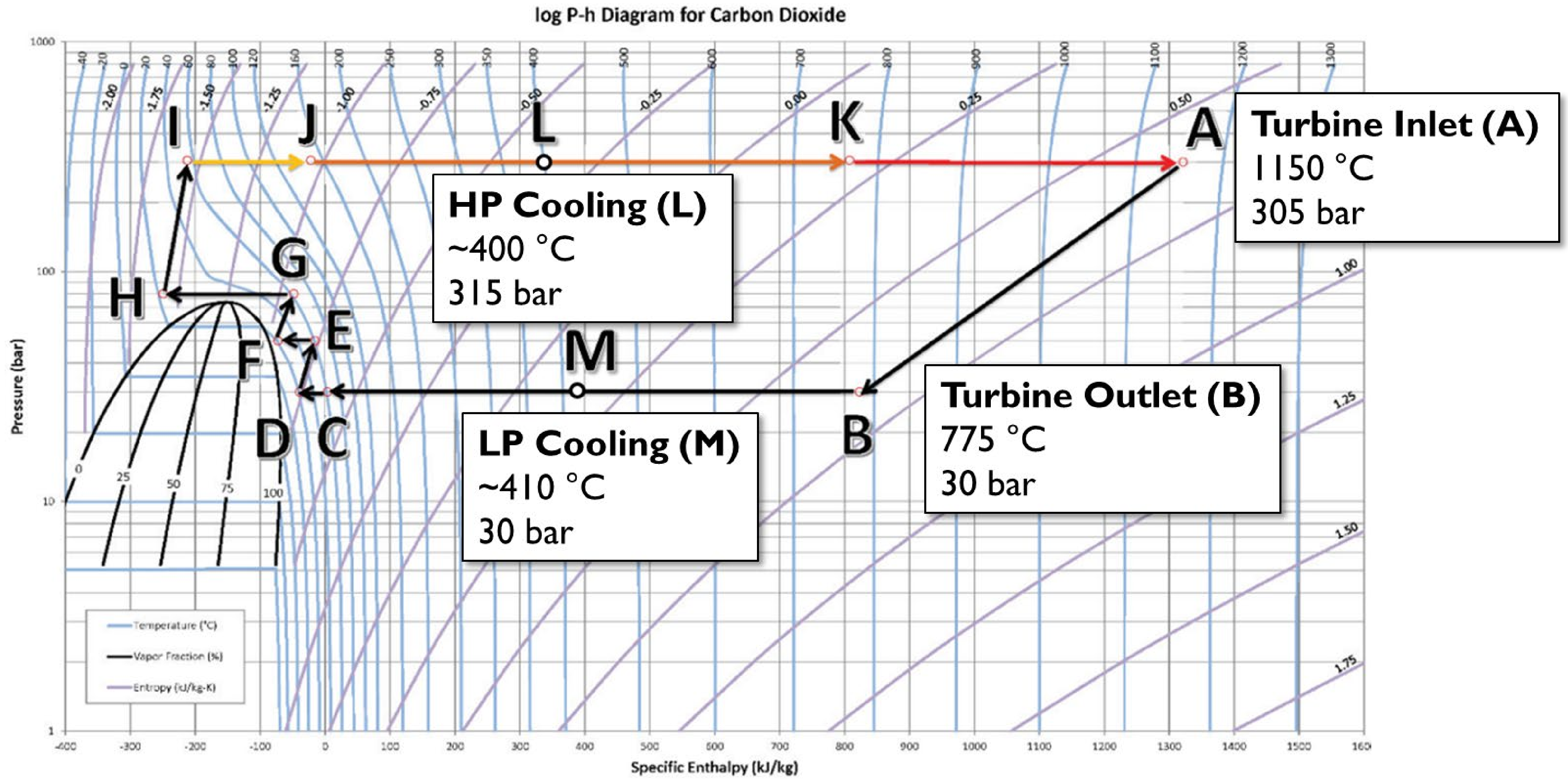
DE-FE0031929

September 24-25, 2024

Development of Syngas Oxy-Combustion Turbine for Use in Advanced sCO2 Power Cycles

- Goal: Develop a detailed design for a sCO_2 direct fired oxy-fuel turbine for utility scale (300 MWe Net, 450 MW turbine power) utilizing a coal syngas fuel, with the ability to be co-fired with natural gas.
- Operation in an Allam-Fetdvedt cycle targets near zero emissions, while targeting 43% LHV system efficiency.
- The density and heat transfer properties of sCO_2 can take advantage of compact turbomachinery and high performing thermal management.
- Technoeconomic analysis performed with turbine costs from detail design

Turbine Conditions



Turbine Inlet (A)
1150 °C
305 bar

HP Cooling (L)
~400 °C
315 bar

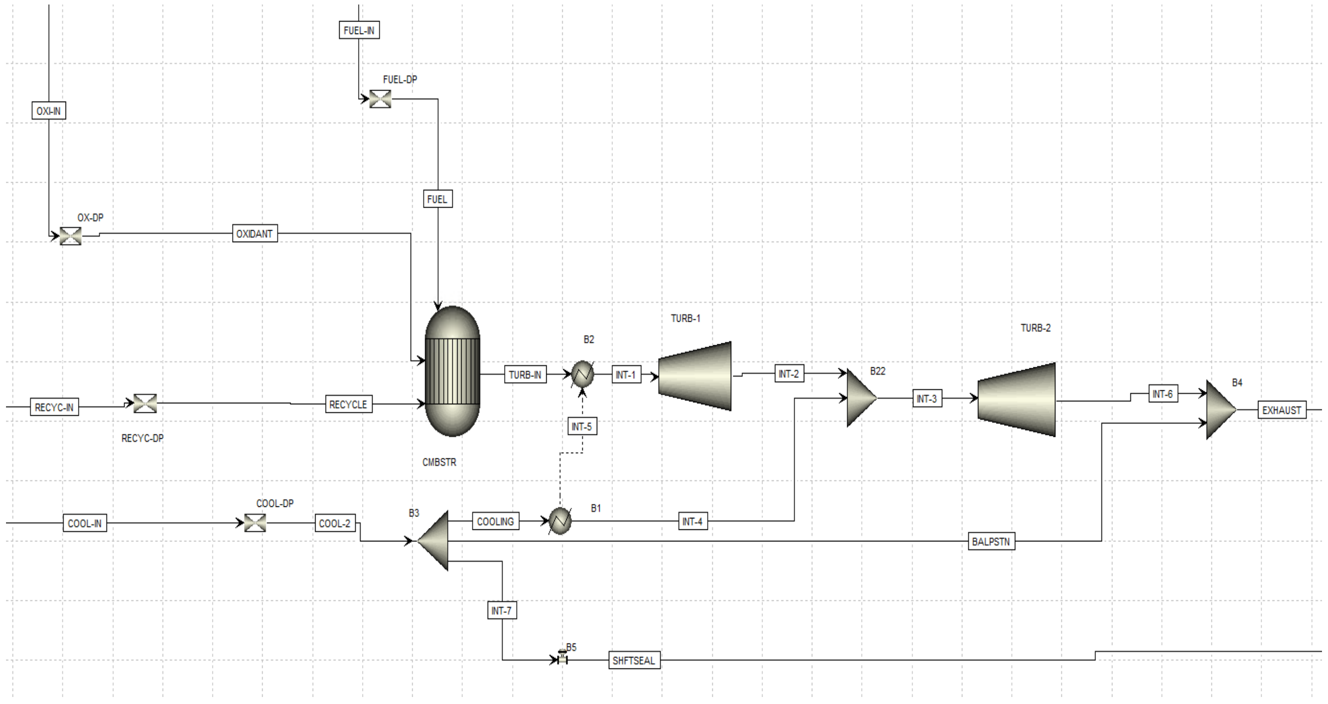
LP Cooling (M)
~410 °C
30 bar

Turbine Outlet (B)
775 °C
30 bar

- How does this compare to steam and gas turbines?
  - Steam (AUSC): 330 bar, 670°C (Source: GE Steam Power)
  - Gas Turbine: 23 bar, 1430°C (Source: GE H-class)

Comparison with NGCC with CCS

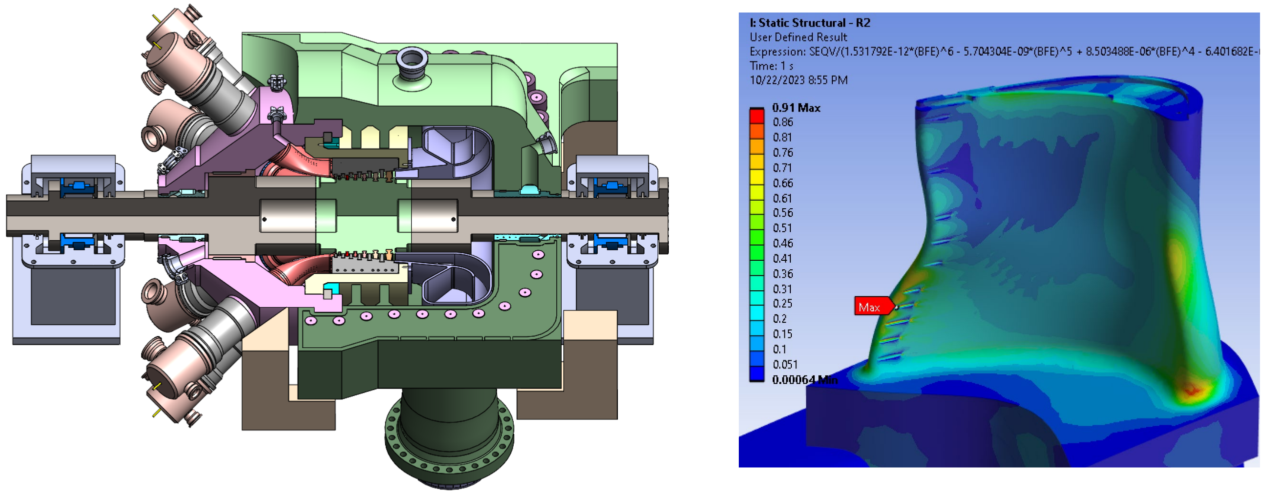
Attribute	NGCC	Oxy-Fuel SCO2
Power generator type	NGCC	Allam with O_2 Storage
CCS plant technology	Amine	CO_2 is Working Fluid
Capital cost $/kW	$1481	$1471
Fixed O&M cost $/kW	$48.96	$48.01
Variable O&M cost $/MWh-net	$3.96	$2.66
Fuel Cost $/MWh-net	$45.87	$43.45*80% =$34.76*
Power generator heat rate (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

Project Components



I: Static Structural - R2
User Defined Result
Expression: SEQV/(1.531792E-12*(BFE)^6 - 5.704304E-09*(BFE)^5 + 8.503488E-06*(BFE)^4 - 6.401682E-
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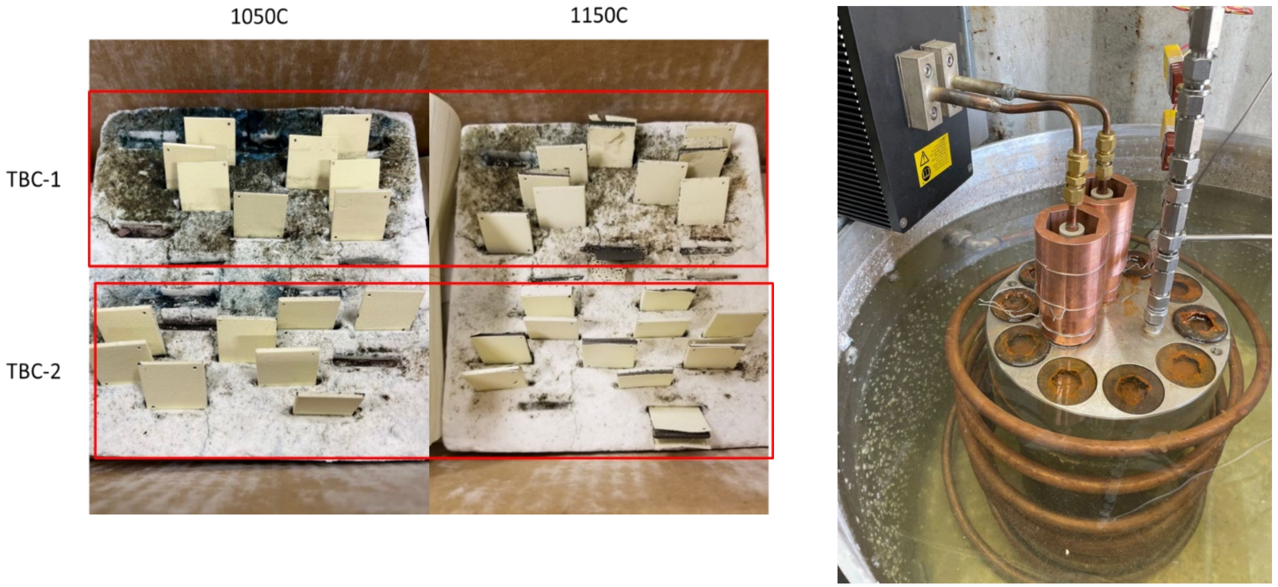
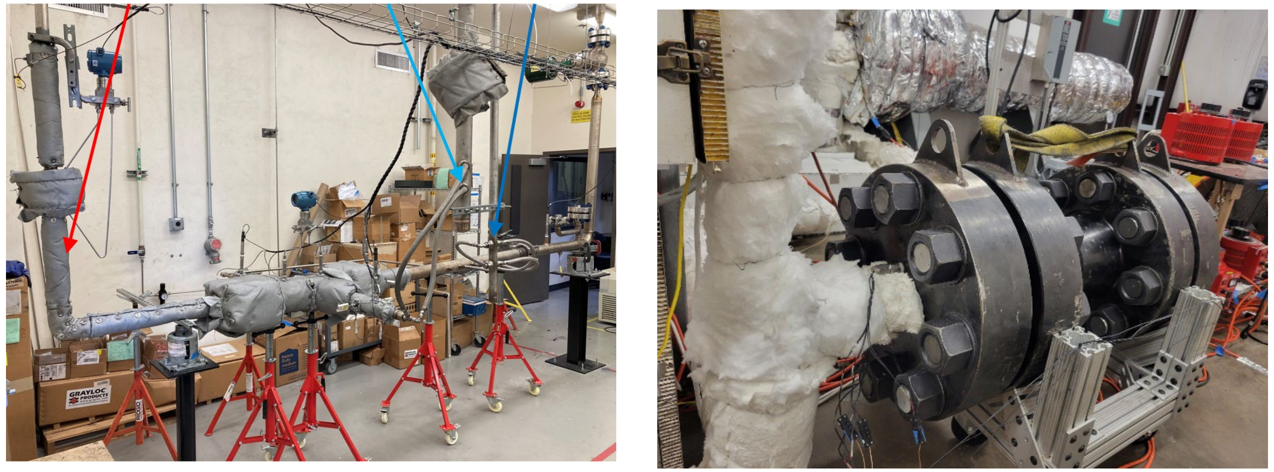
Turbine Design



Materials Testing



Component Testing

Project Team

SwRI: PI, Heat transfer testing, materials testing, turbine design.

GE: Aerodynamic flowpath definition, design support.

Purdue: Turbine first stage optimization, blade cascade testing.

UCF: Pin fin, impingement heat transfer testing.

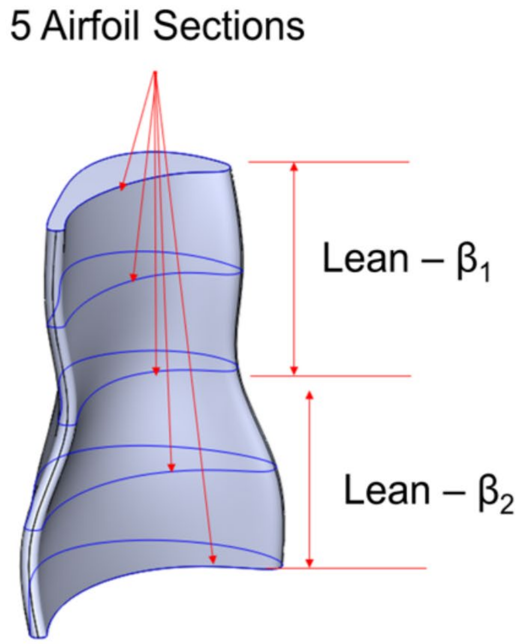
8 Rivers: Thermodynamic cycle model.

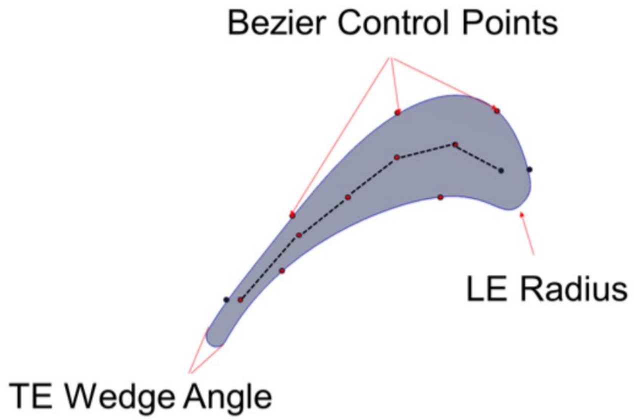
EPRI: Technoeconomic study.

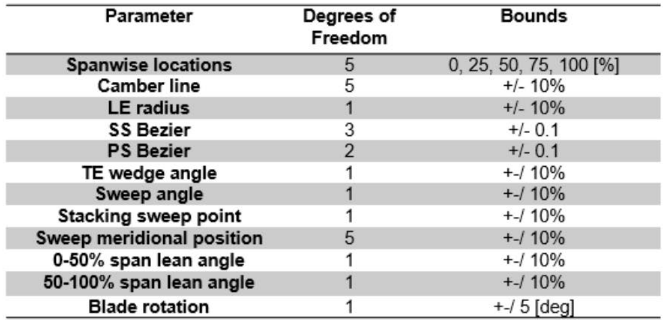
Air Liquide: Oxy-combustor development.

Component Testing

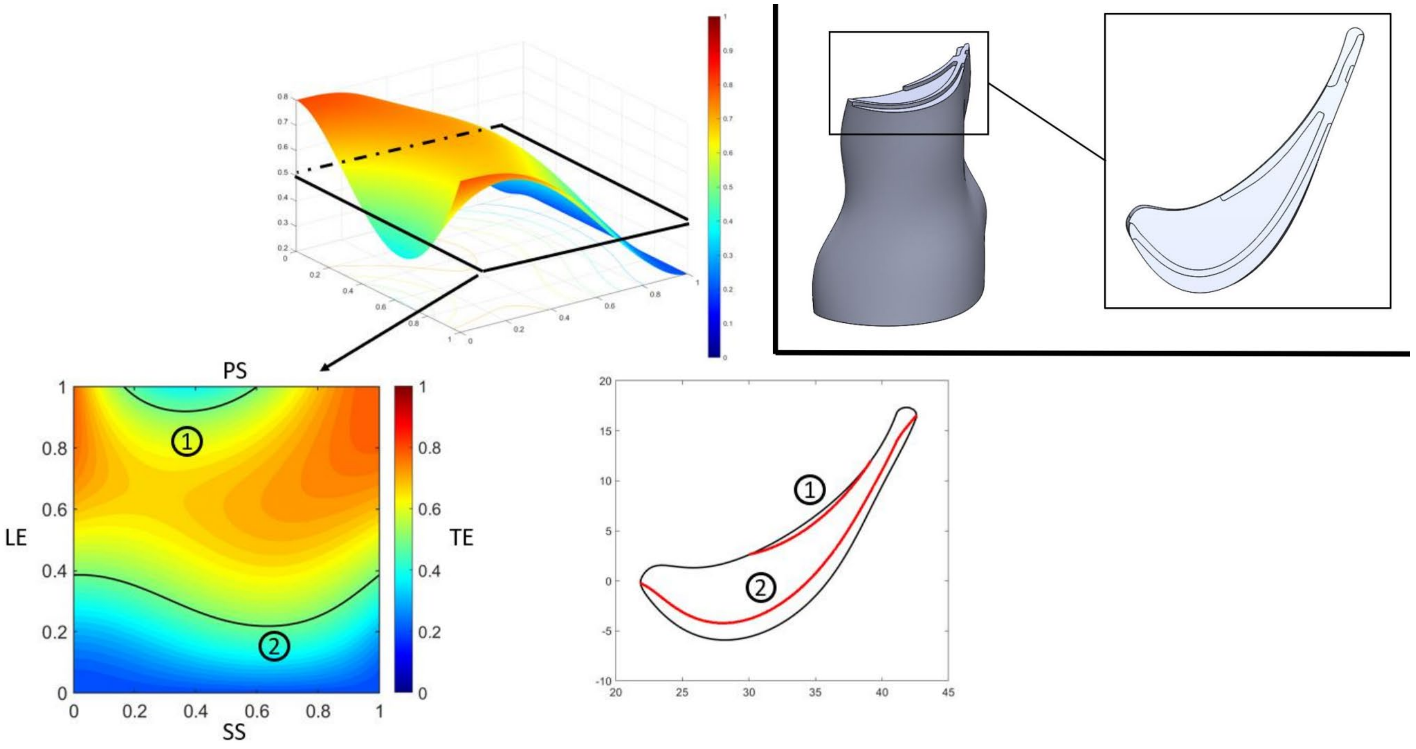
Background on 1st Stage Blade Optimization





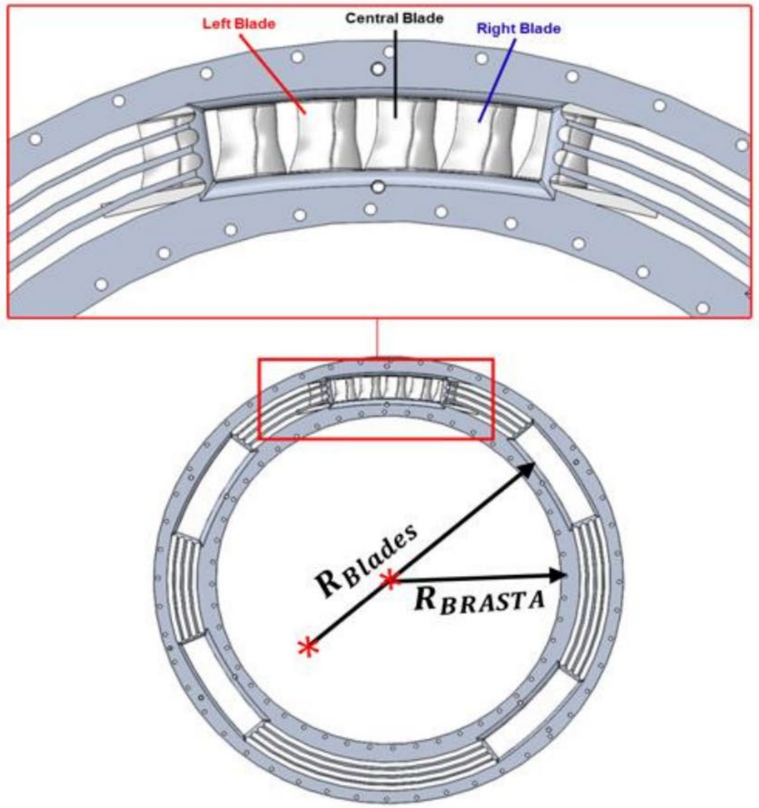


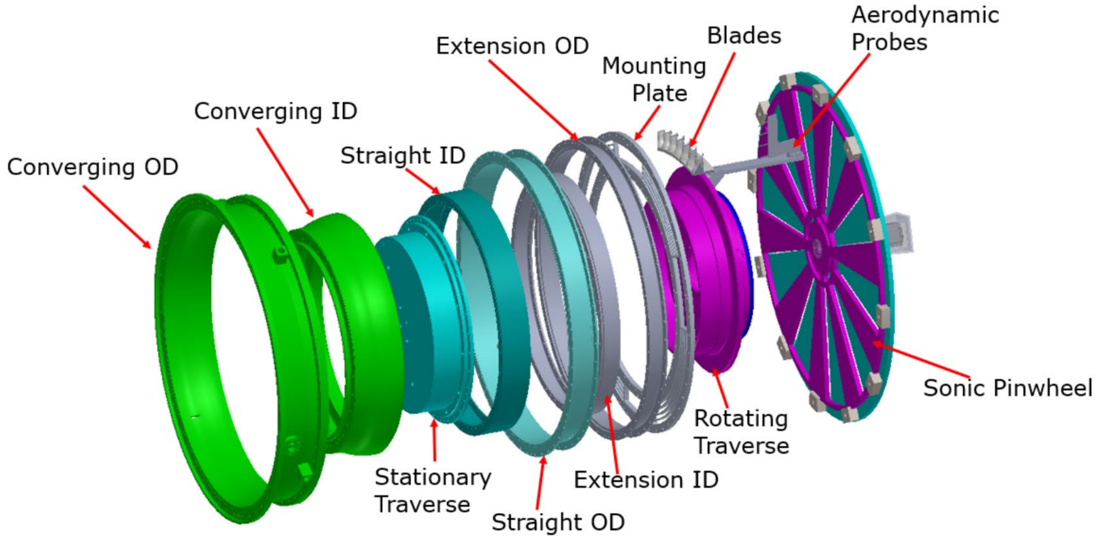
Parameter	Degrees of Freedom	Bounds
Spanwise locations	5	0, 25, 50, 75, 100 [%]
Camber line	5	+/- 10%
LE radius	1	+/- 10%
SS Bezier	3	+/- 0.1
PS Bezier	2	+/- 0.1
TE wedge angle	1	+-/ 10%
Sweep angle	1	+-/ 10%
Stacking sweep point	1	+-/ 10%
Sweep meridional position	5	+-/ 10%
0-50% span lean angle	1	+-/ 10%
50-100% span lean angle	1	+-/ 10%
Blade rotation	1	+-/ 5 [deg]



- Purdue University has led the optimization of the 1st stage blade from GE mean line design, optimizing for efficiency and heat load.
- Best Paper Award at 2024 sCO_2 Symposium: Tuite, et. al., "Blade and Rim Seal Design of a First Stage High Pressure Turbine for a 300 MWe Supercritical CO2 Power Cycle".

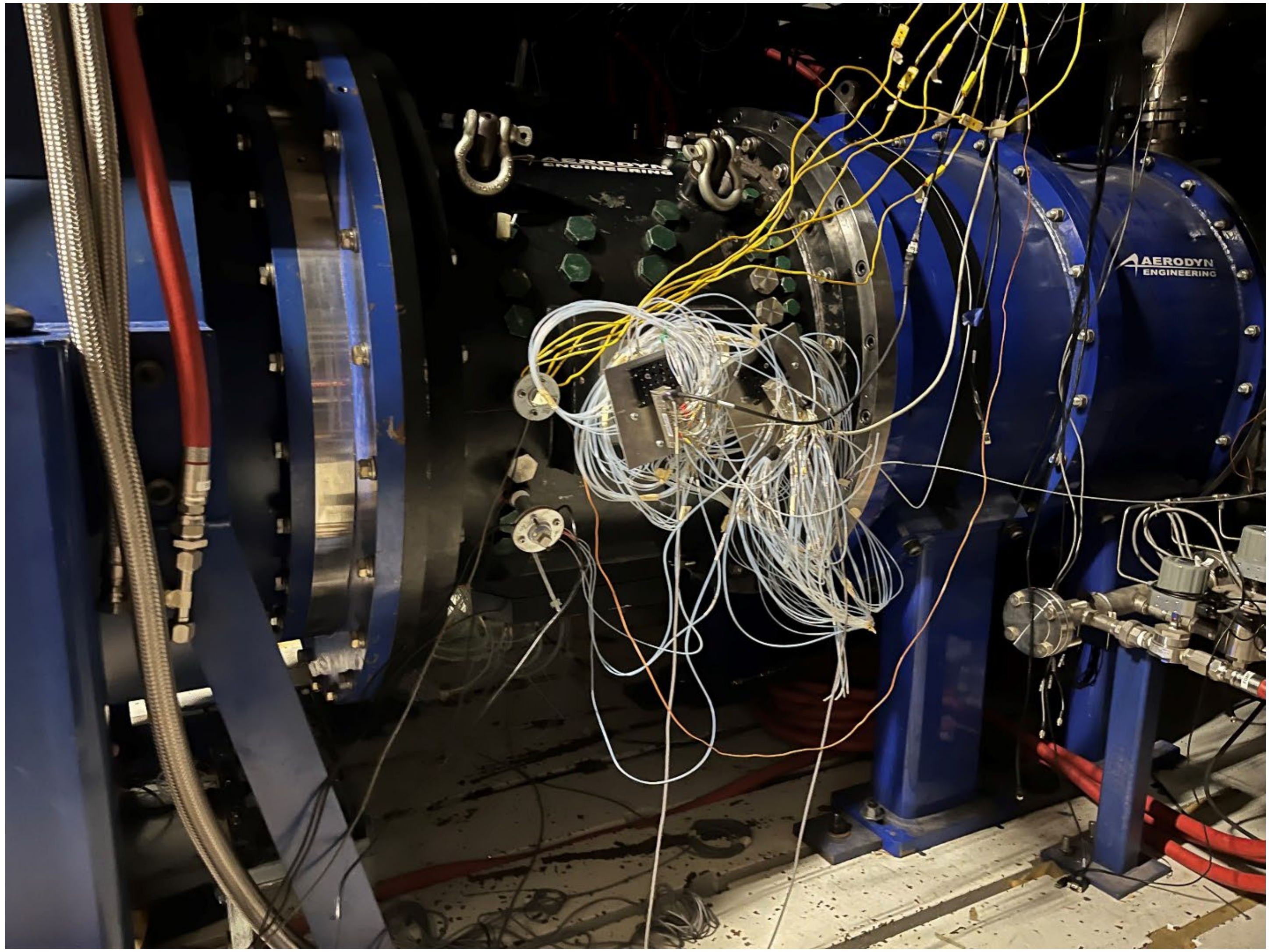
S1B cascade testing setup



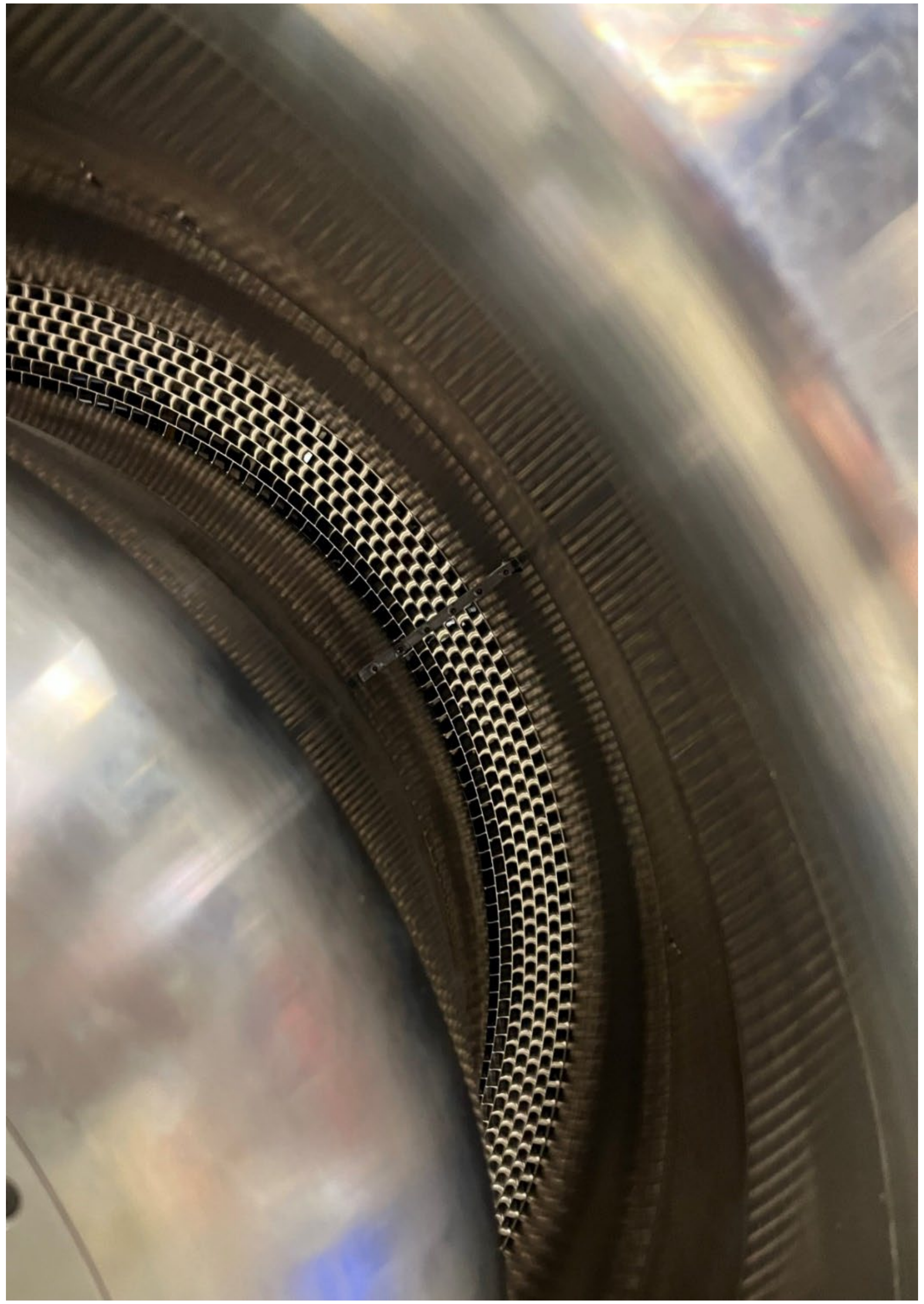


- The Purdue Big Rig for Aerothermal Stationary Turbine Analysis (BRASTA) was utilized with modifications for a S1B cascade test.

Test Rig – S1B Cascade Test



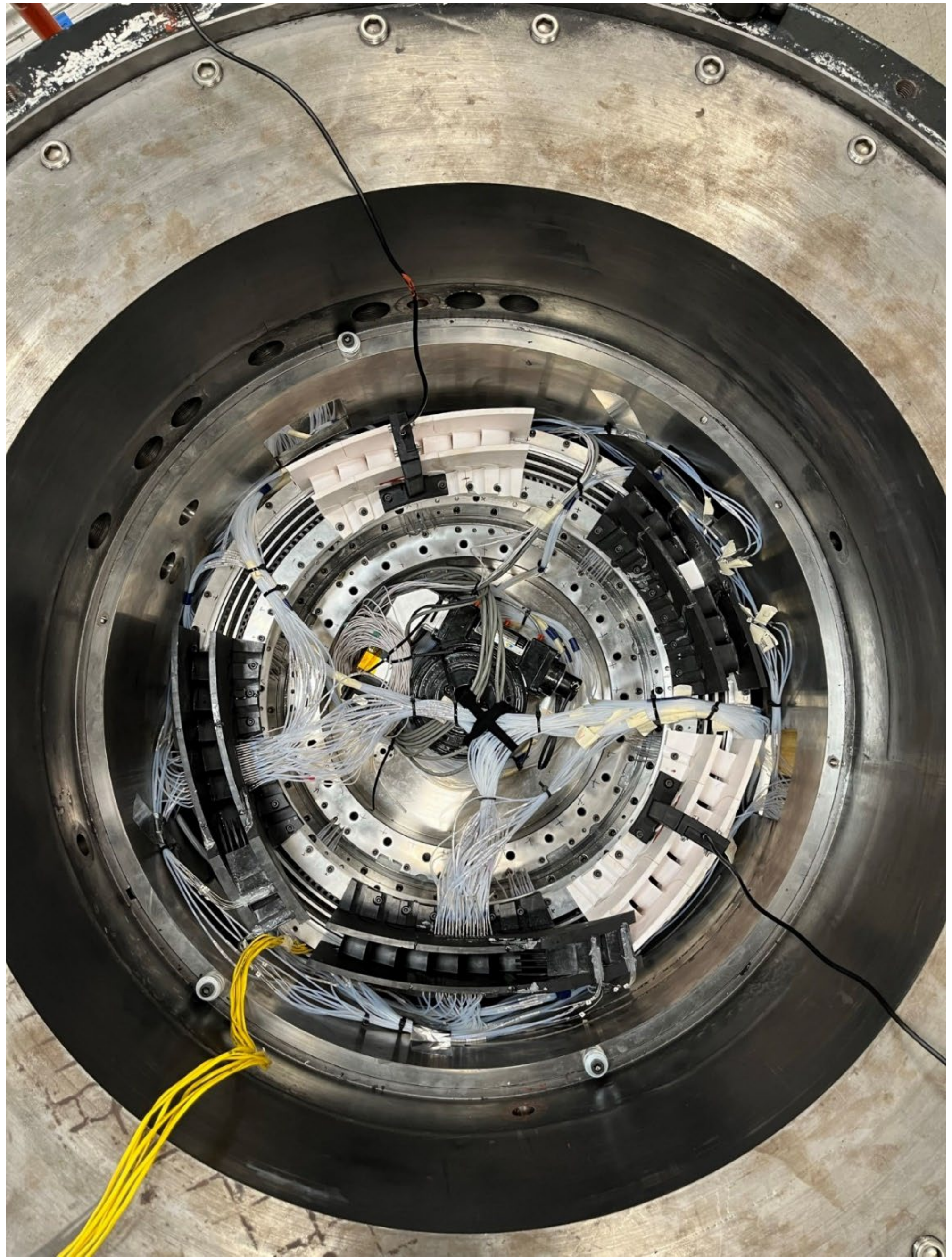
Fully-assembled Purdue BRASTA with blades and instrumentation assembled internally.



Inlet pressure rake upstream of flow-conditioning gauze.

Test Rig – S1B Cascade Test

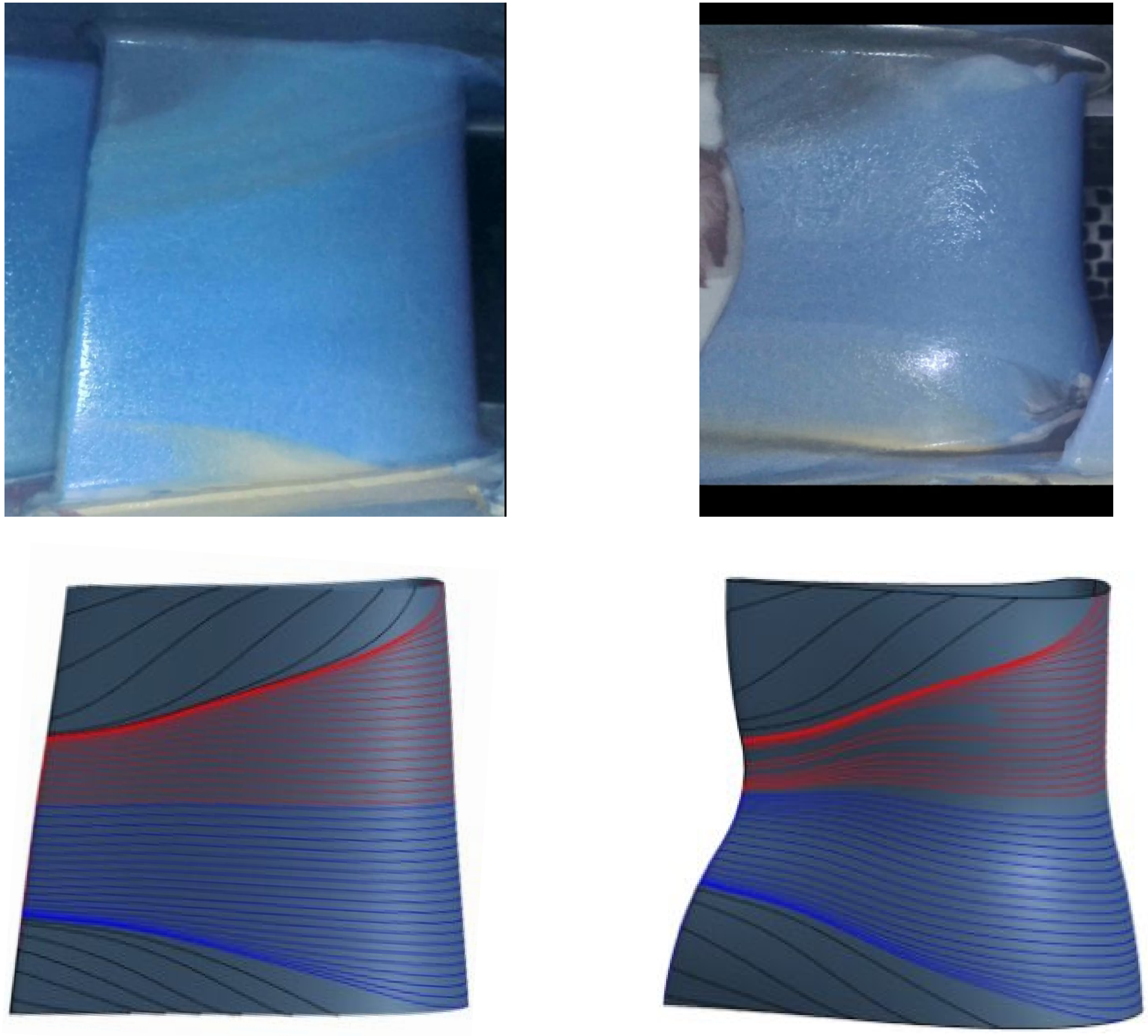
Sonic plate actuation downstream of the test section allows for modulation of flow rate/Reynolds number.



Instrumented blade section including pressure tapped section (6 o'clock, 9 o'clock) and oil vis sections (12 o'clock, 4 o'clock) for baseline and optimized blades.

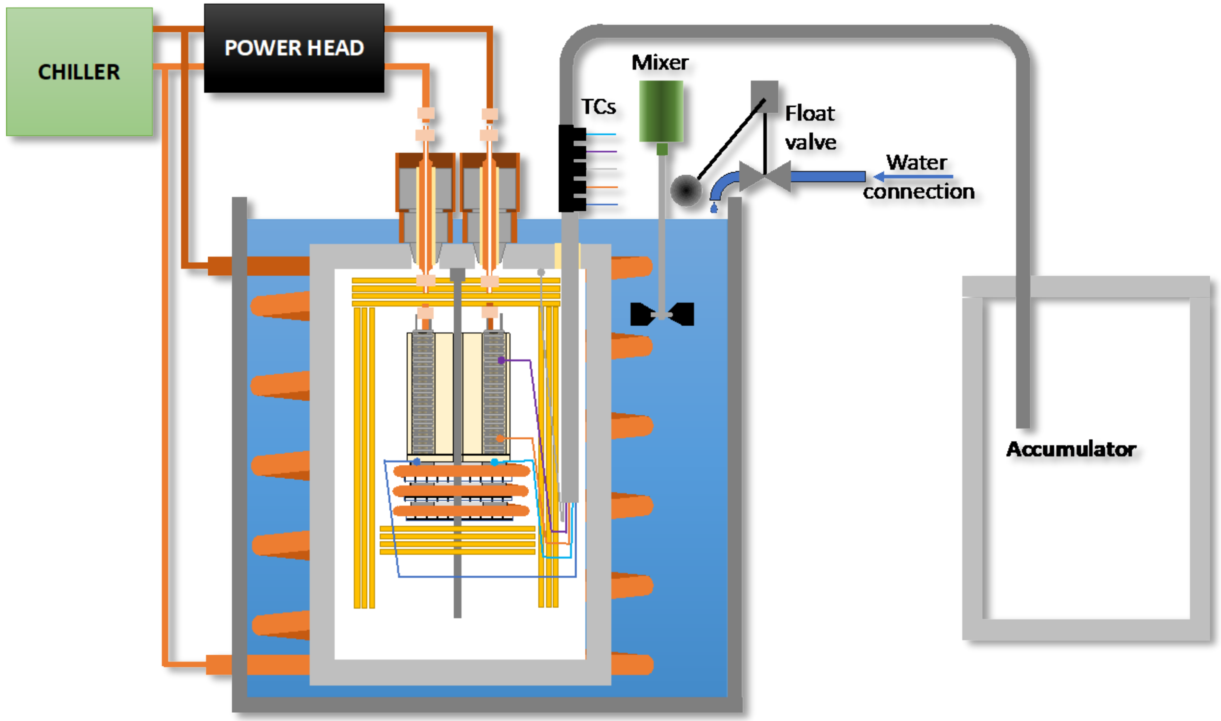
Test Rig – S1B Cascade Test

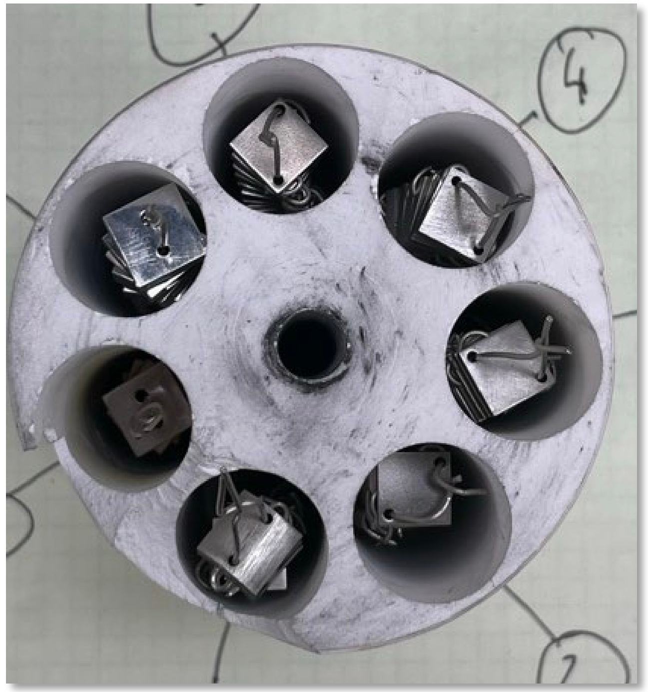
- Oil visualization with pigmented oils is used for both the baseline and optimized blade geometries.
- Agreement seen between shear stress contours in experiment and CFD predictions.



Materials Testing

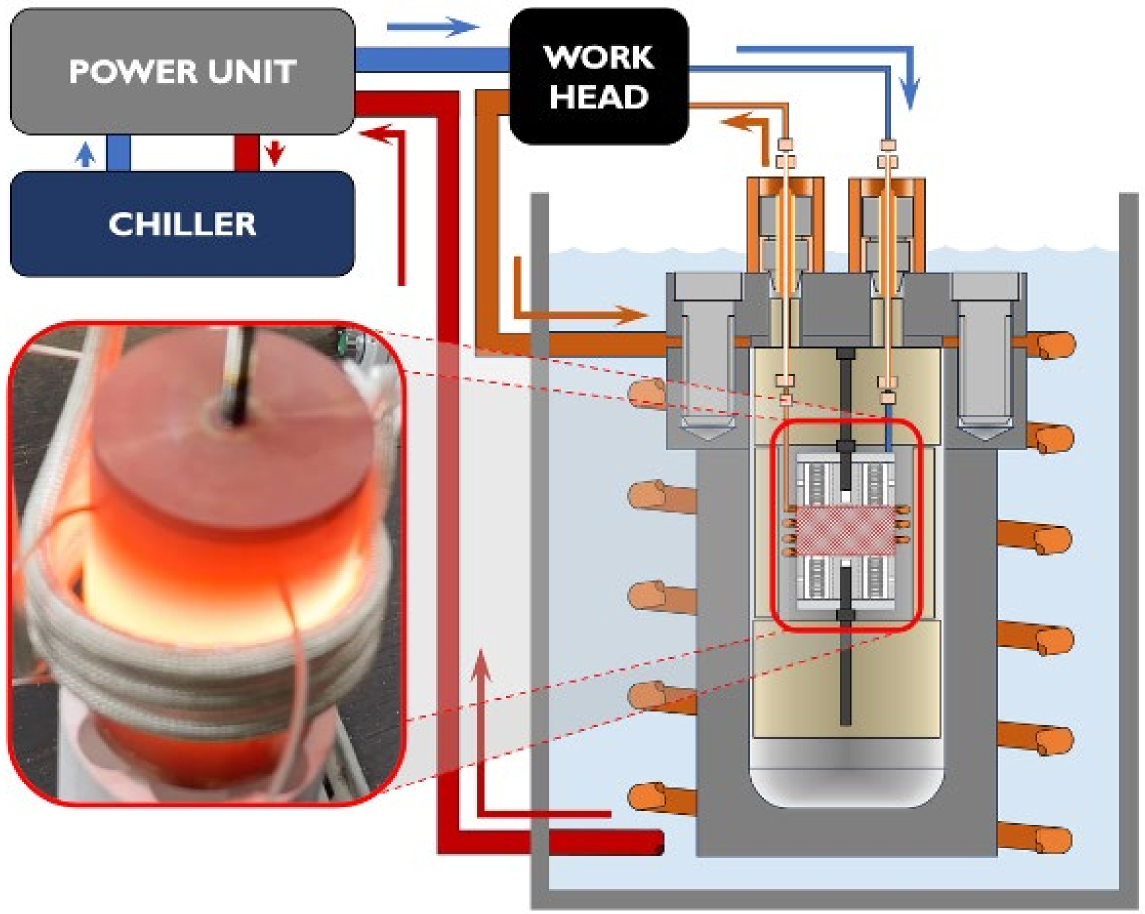
Autoclave Testing – Initial Setup

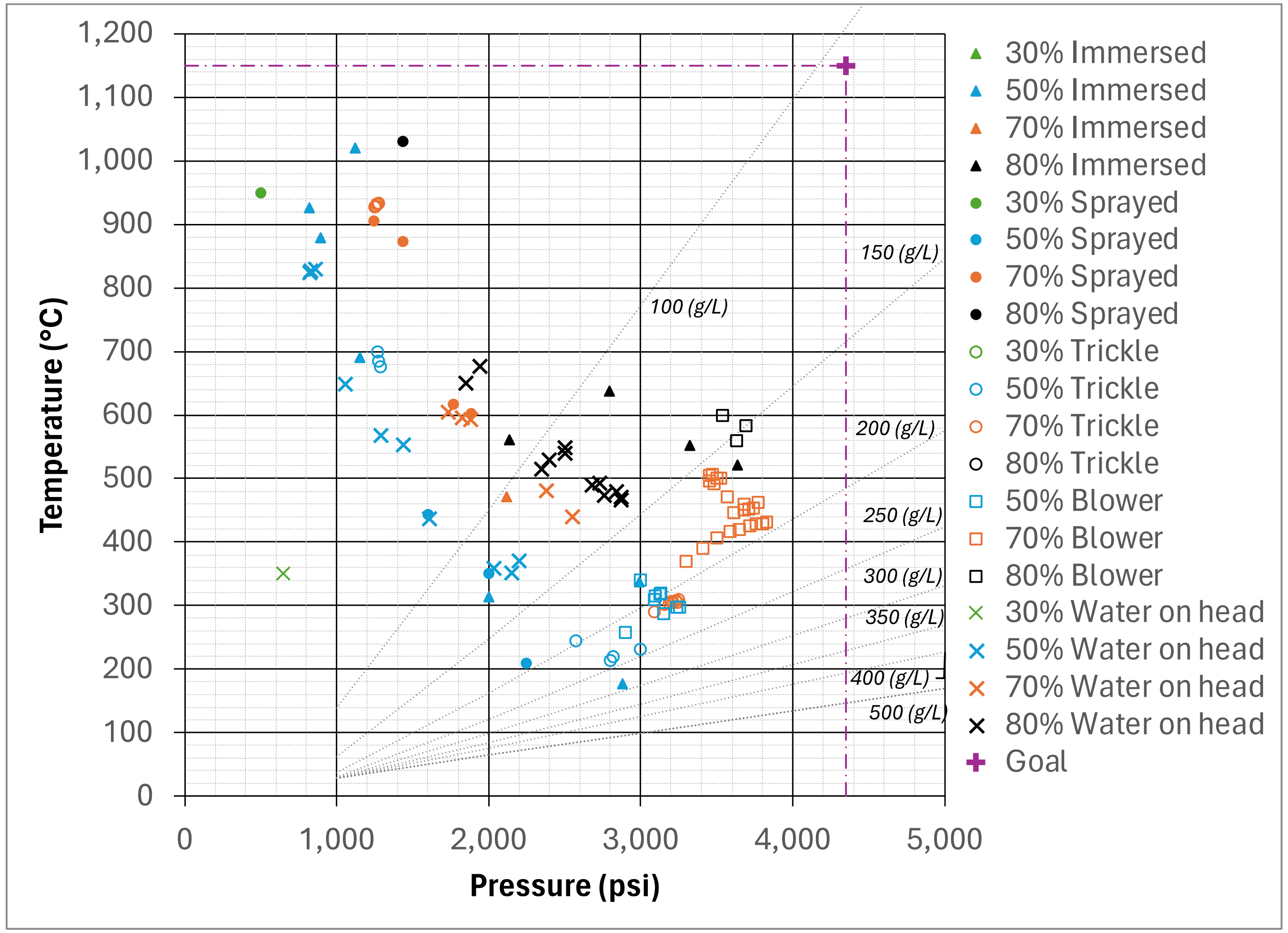




- Autoclave tests are for material and coatings exposure and oxidation characteristics observation at turbine inlet conditions.
- An induction heater with susceptor is employed with TCs inserted to measure temperature throughout stack of material samples.

Autoclave Testing – Revised design



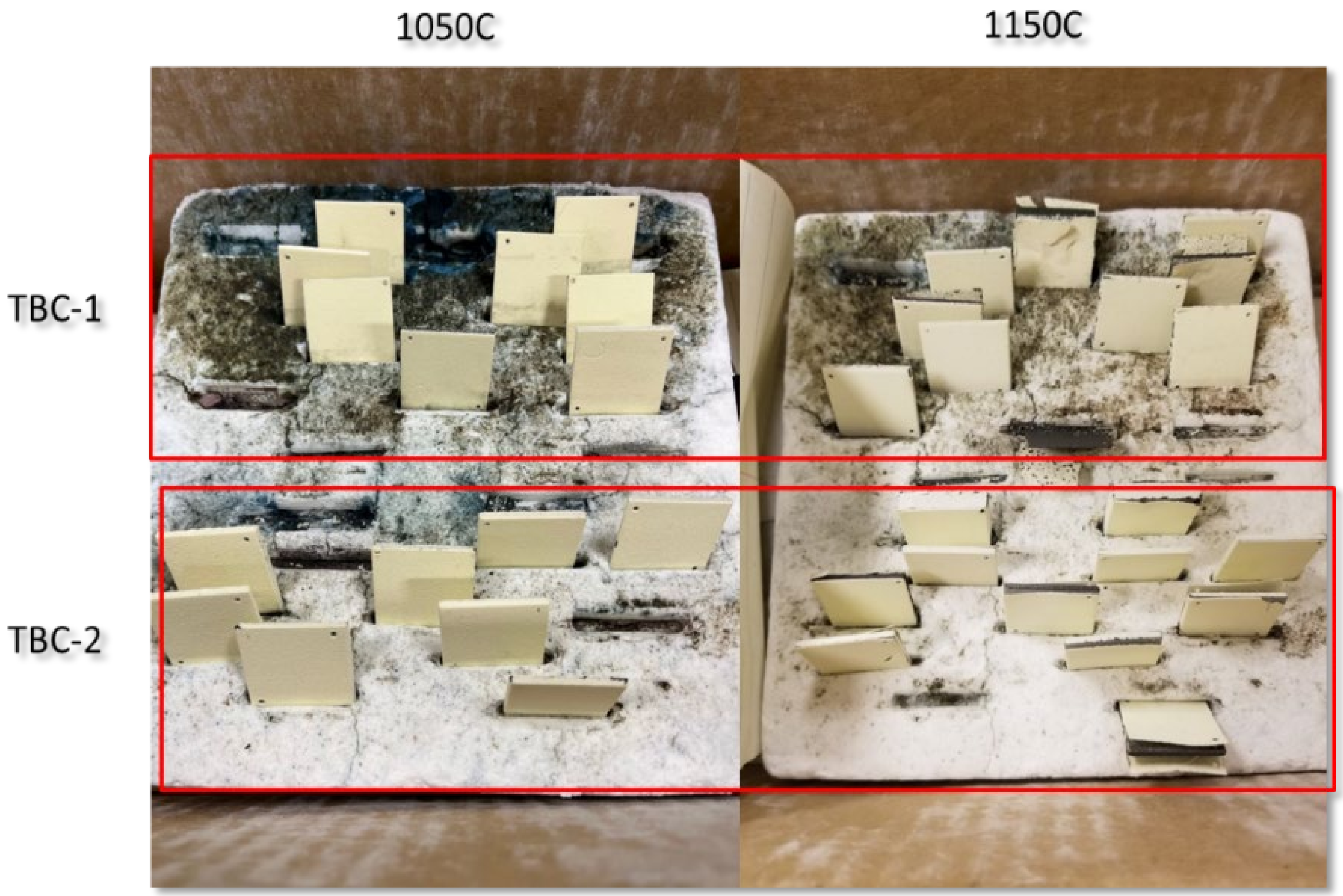


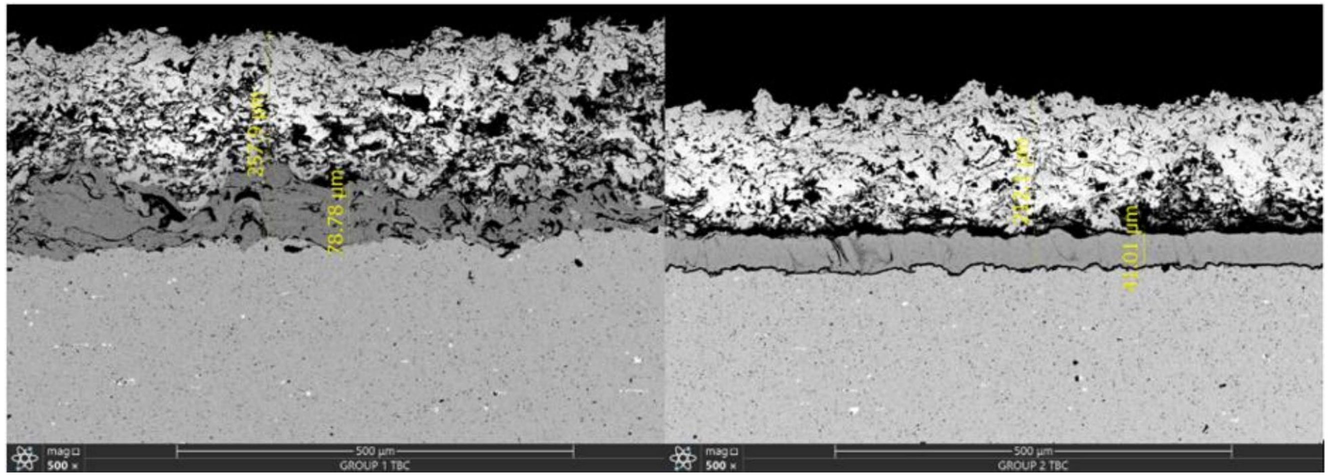
- Monolithic 310S specimen holder and susceptor.
- Improved reliability compared to graphite susceptor, decreased resistivity has led to lower temperatures achieved. *Requires modifications to setup for decreased heat leak.*

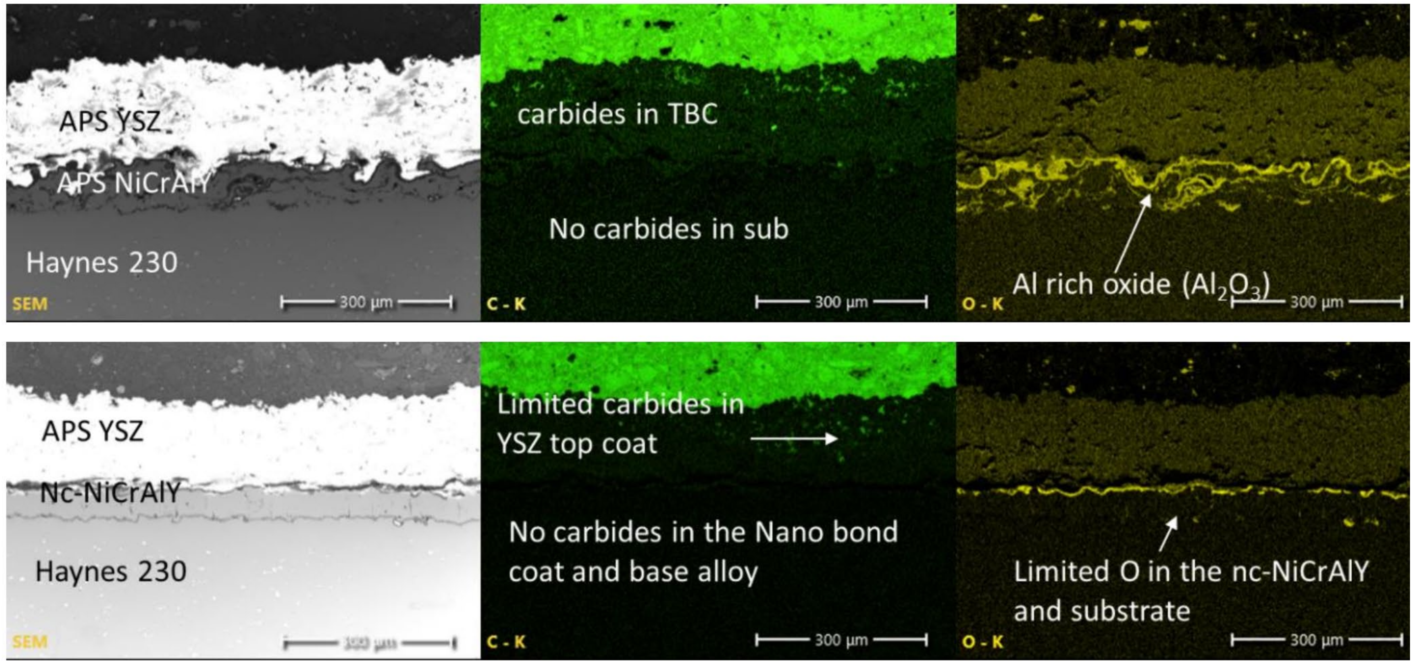
Autoclave Testing – Current status

- **September 2024**: Completion of test setup modifications to improve insulation and reduce heat loss from specimen holder region of autoclave.
- **Beginning October 2024**: Complete remaining 5,000 hr. testing at temperatures up to 1200°C and pressures up to 300 bar to represent turbine inlet conditions.

TBC Cyclic Testing - Recap

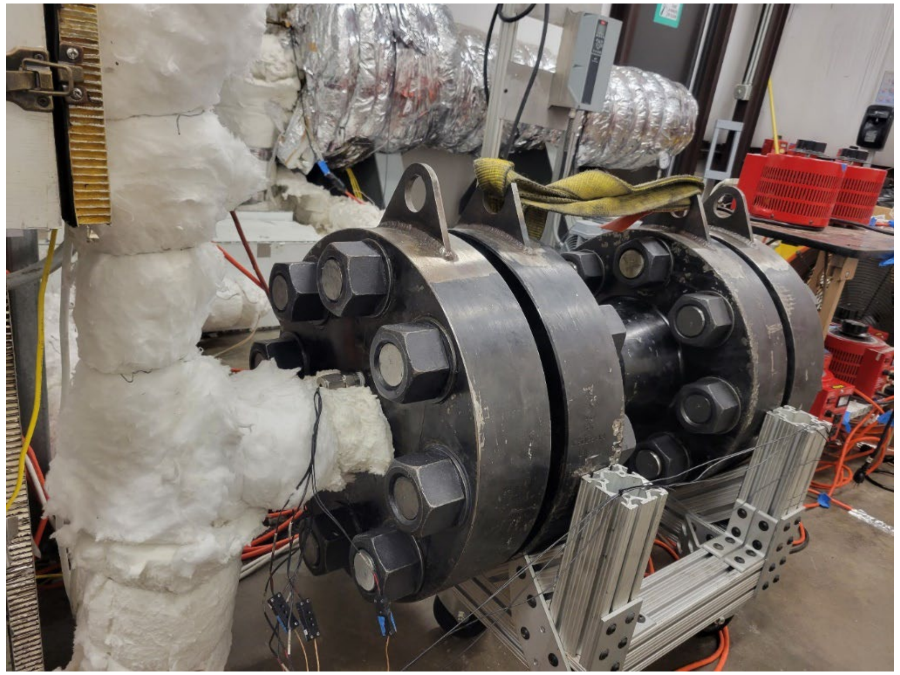


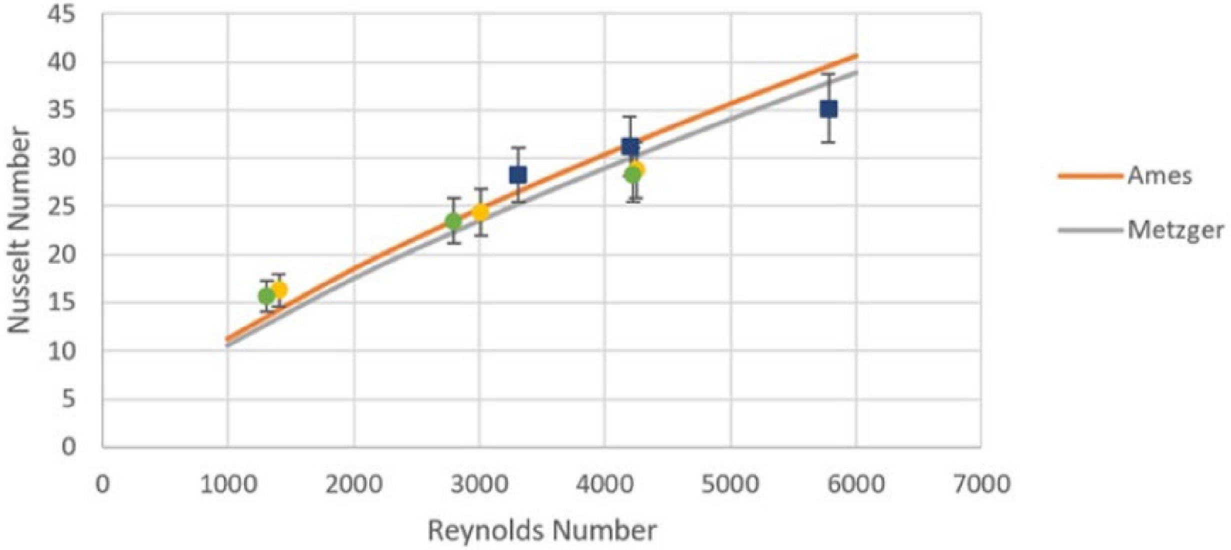




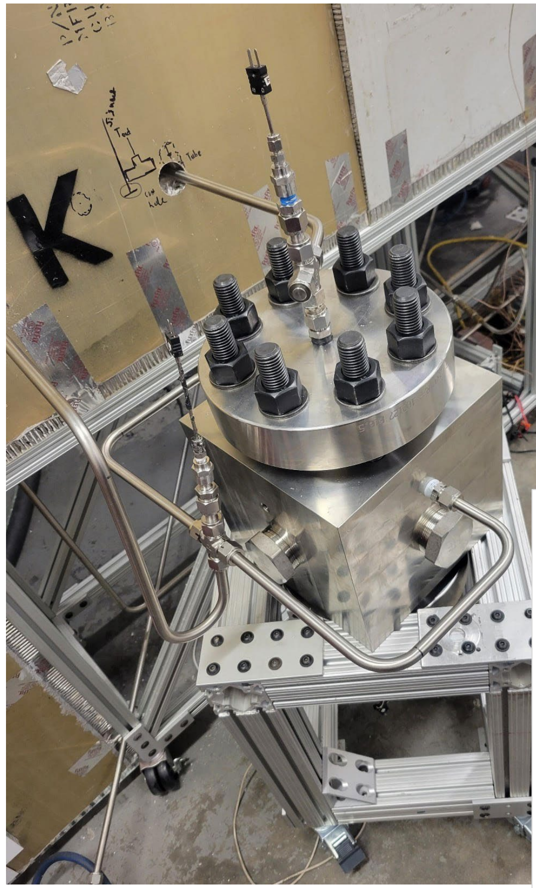
- Tests performed in 2023 included different TBC coating methods on Haynes 230 for 500 cycles (50 min. at temperature, 10 min. forced air cooling).
  - TBC-1:*Thermal spray* MCrAlY bond coat, *thermal spray* yttrium stabilized zirconia (YSZ) top coat.
  - TBC-2: Plasma Enhanced Magnetron Sputtering (*PEMS*) MCrAlY bond coat, thermal sprayed (YSZ) top coat.

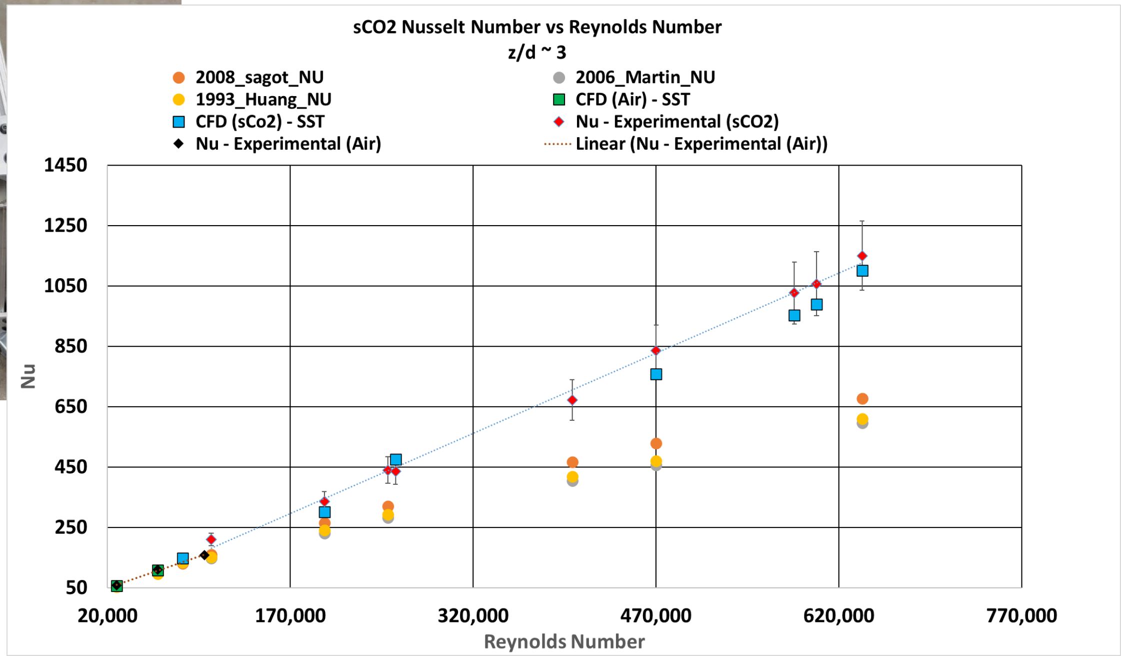
Experiments – Impingement and pin-fin heat transfer





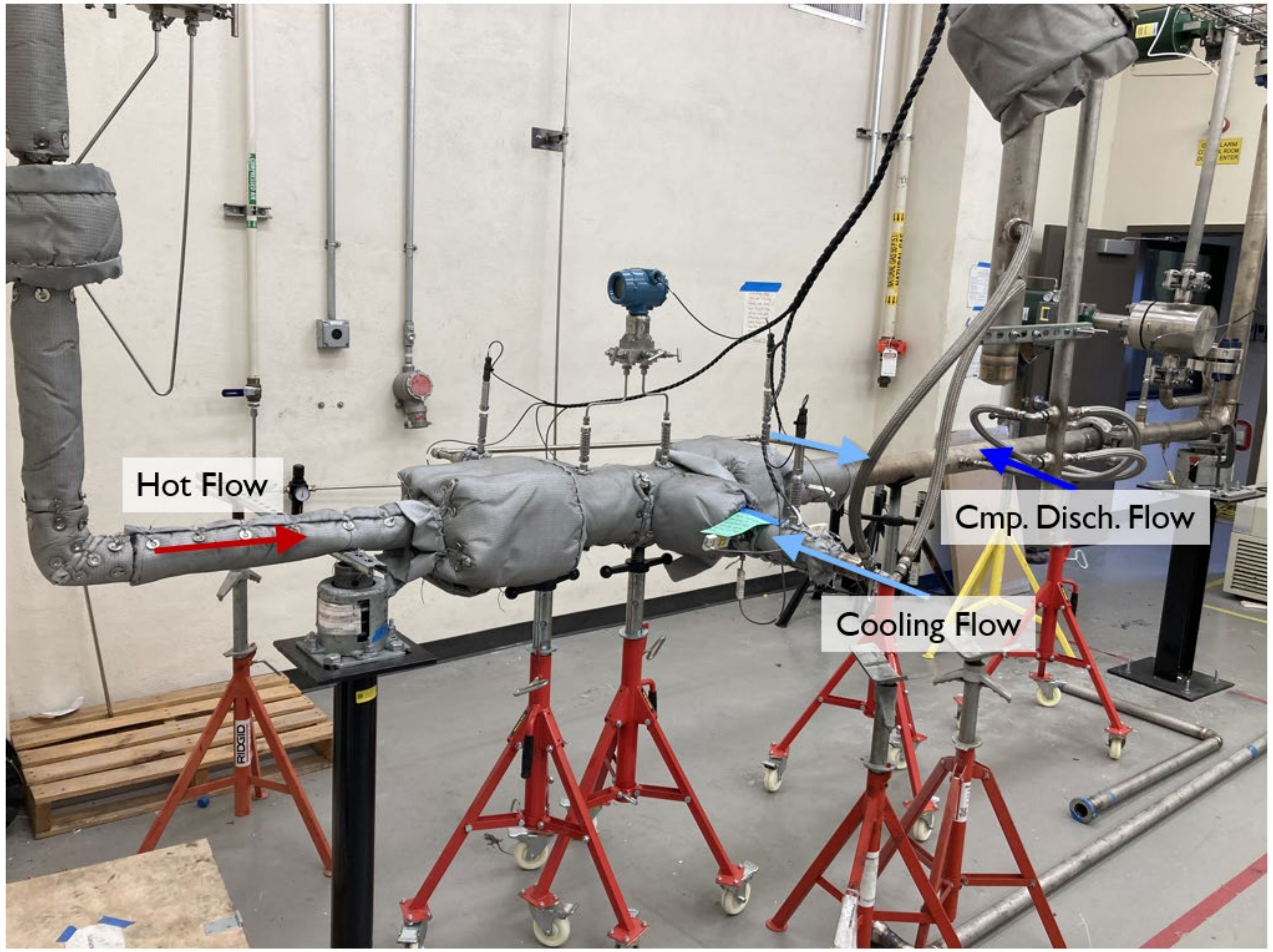
Testing at UCF (2022): Pin-fin heat transfer in sCO_2 shows alignment with Metzger correlation.

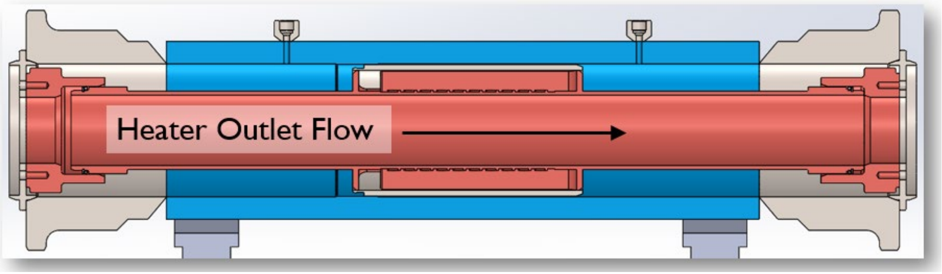


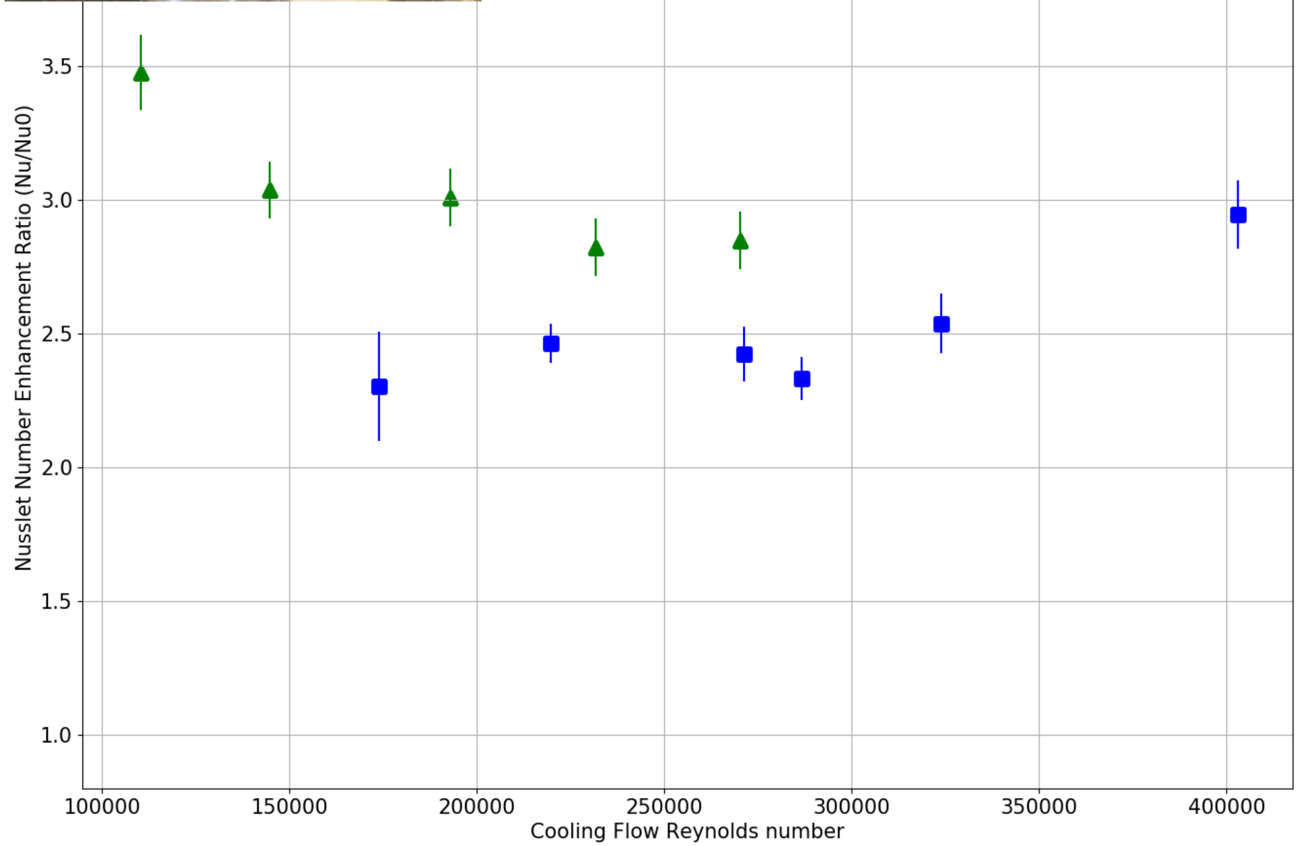


Testing at UCF (2022): Impingement data in sCO_2 demonstrates cautionary use with certain correlations based on air data.

Experiments – Mid-section serpentine cooling



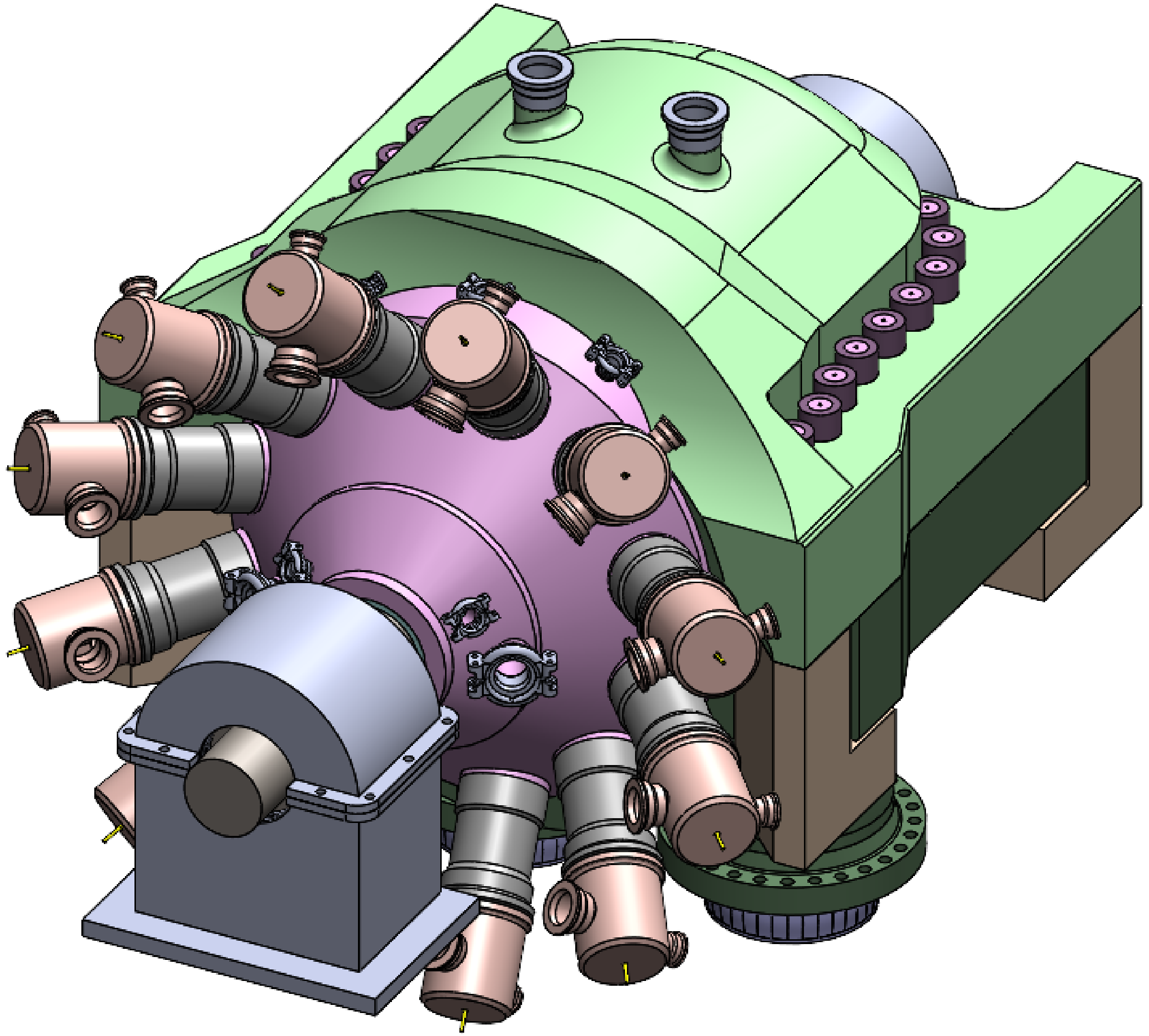


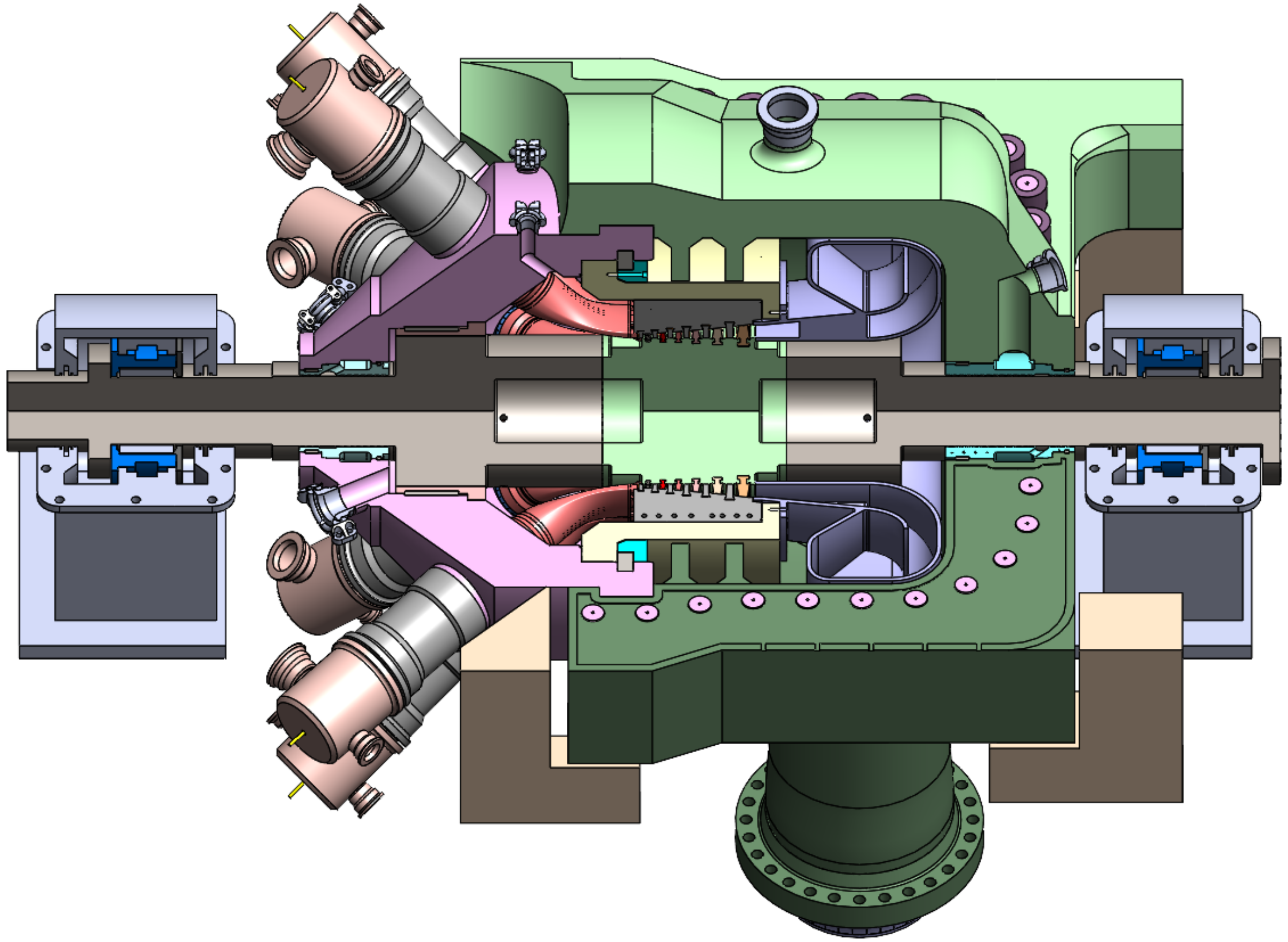


Testing at SwRI (2023): Mid-section serpentine cooling heat transfer in sCO_2 produced Nusselt number enhancement ratios, over a Reynolds number range exceeding relevant existing literature.

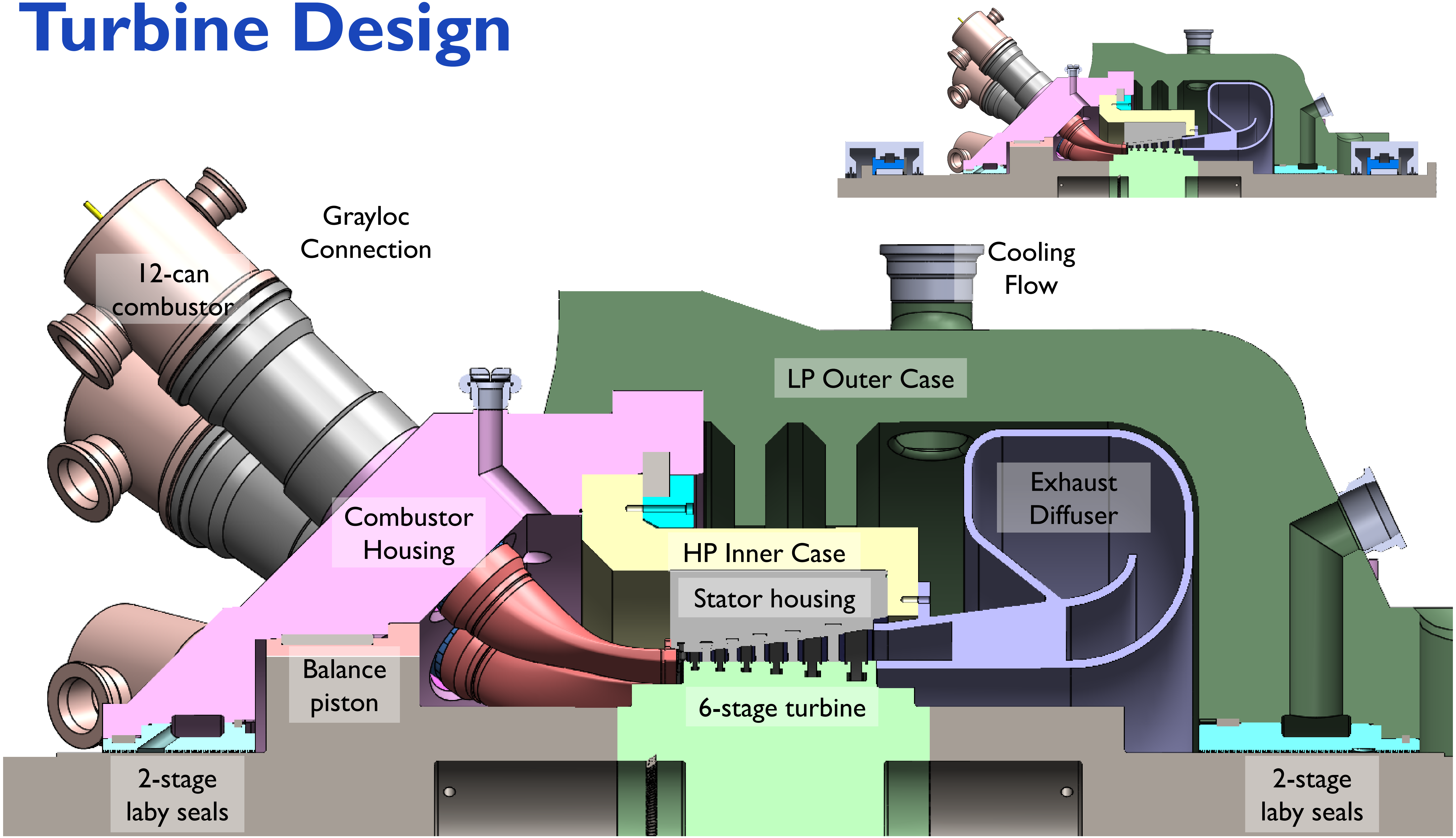
Turbine Design

Turbine Design

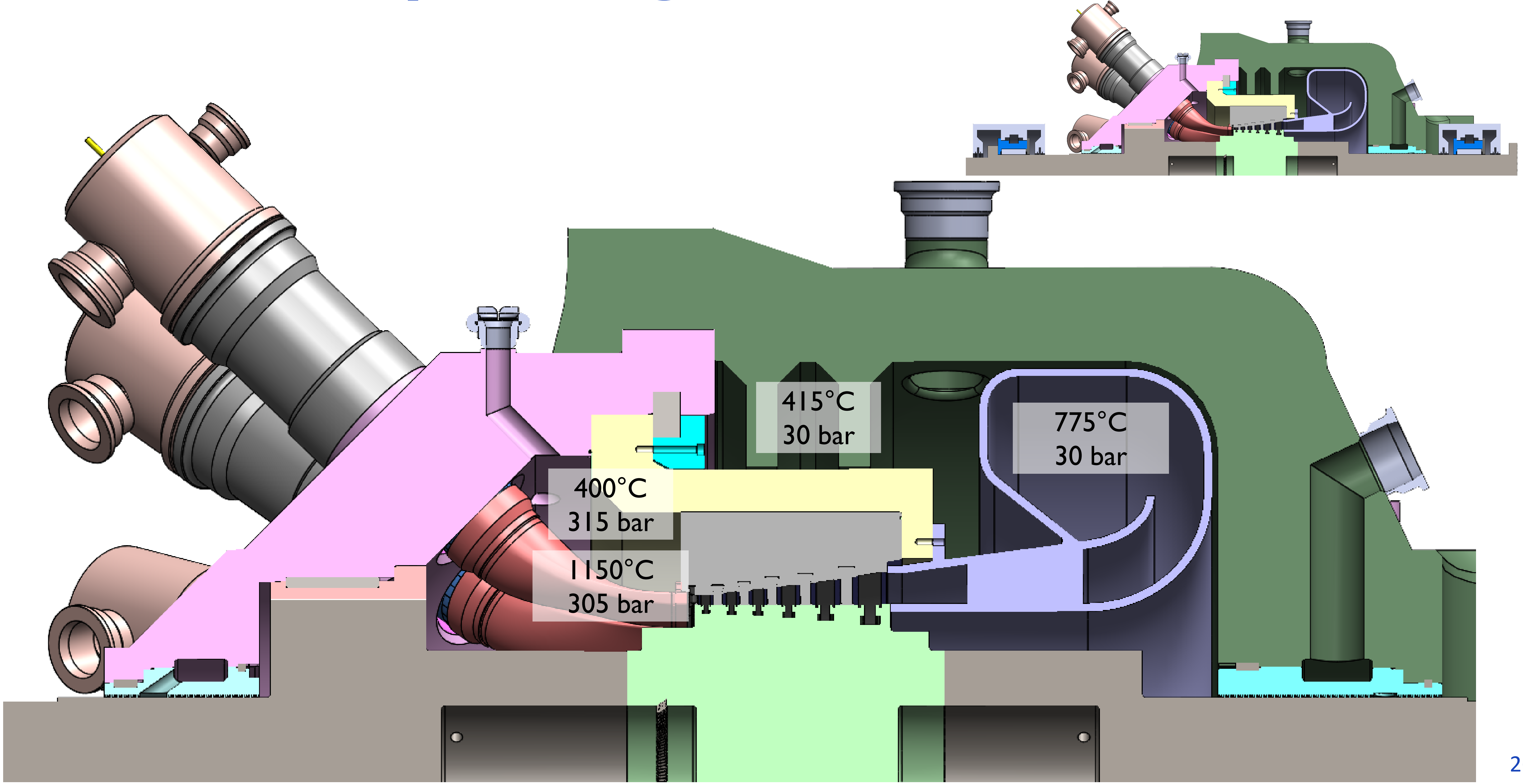




Turbine Design

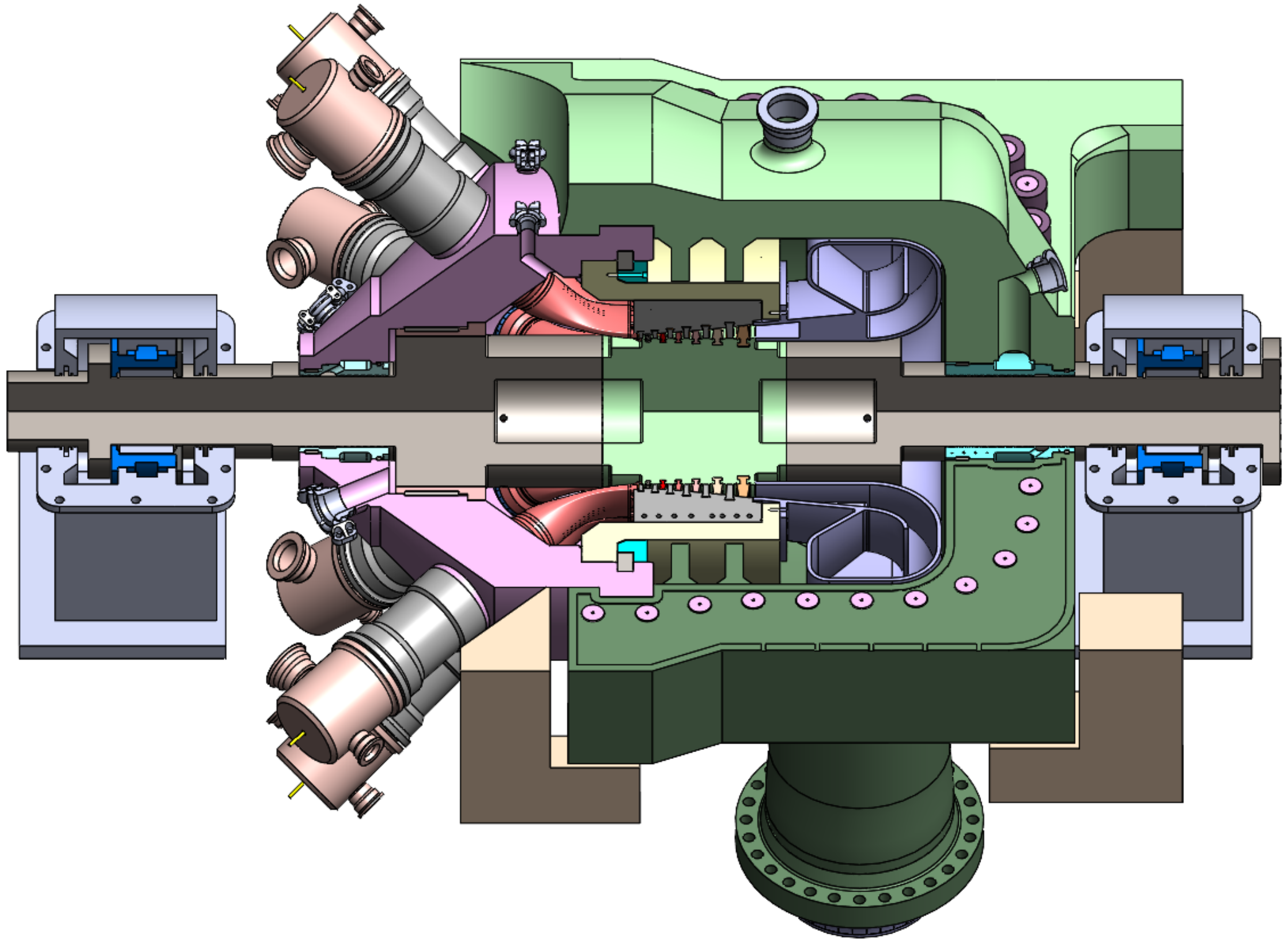


Standard Operating Conditions



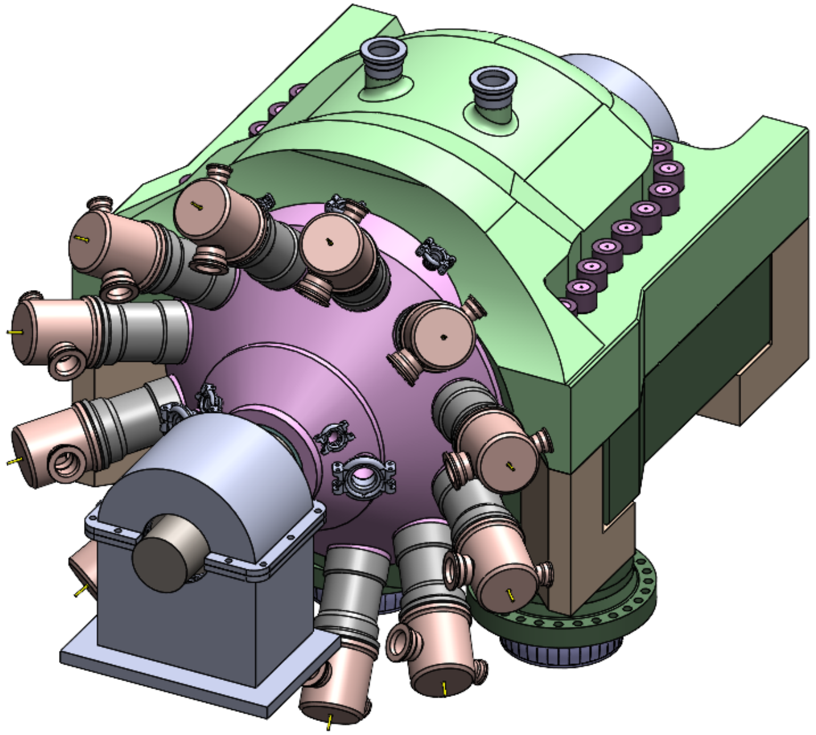
Target Design Criteria

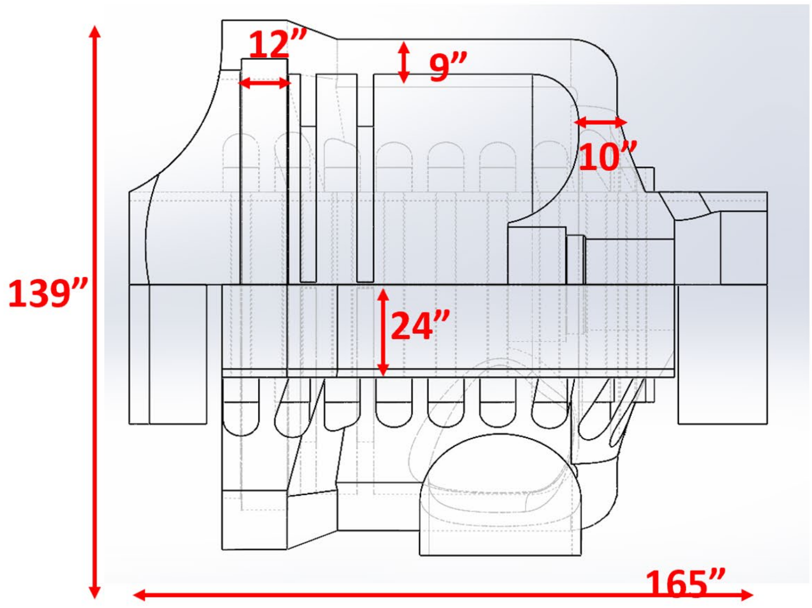
- Hot section component lifetime (combustor, transition duct, S1N, S1B): **30k hrs**
- Rotor lifetime: **150k hrs**
- Pressure containing components designed to ASME BPVC, Section VIII.
- Rotordynamics completed according to API standards.
- Mitigate capital cost through the following strategies:
  - Minimize wetted area of HP sections to *minimize required section thickness and sealing force.*
  - Use cooling flow routing to jacket large diameter components to use *chrome steels below their creep regime.*

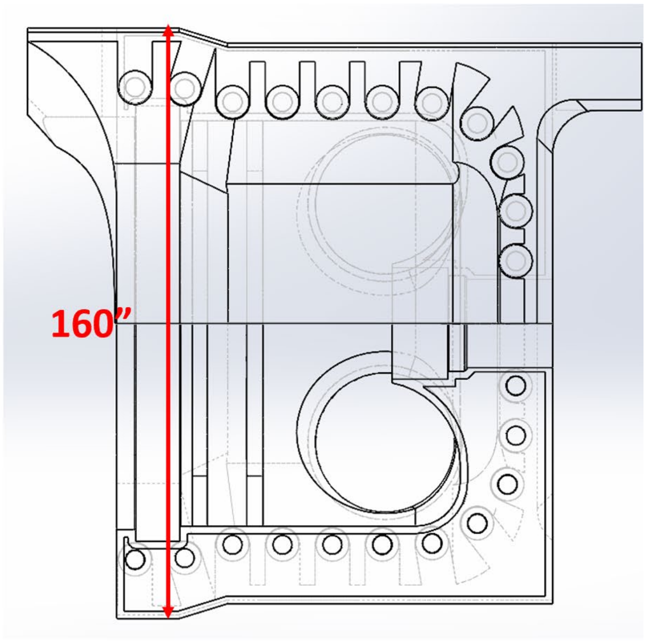


Case Design

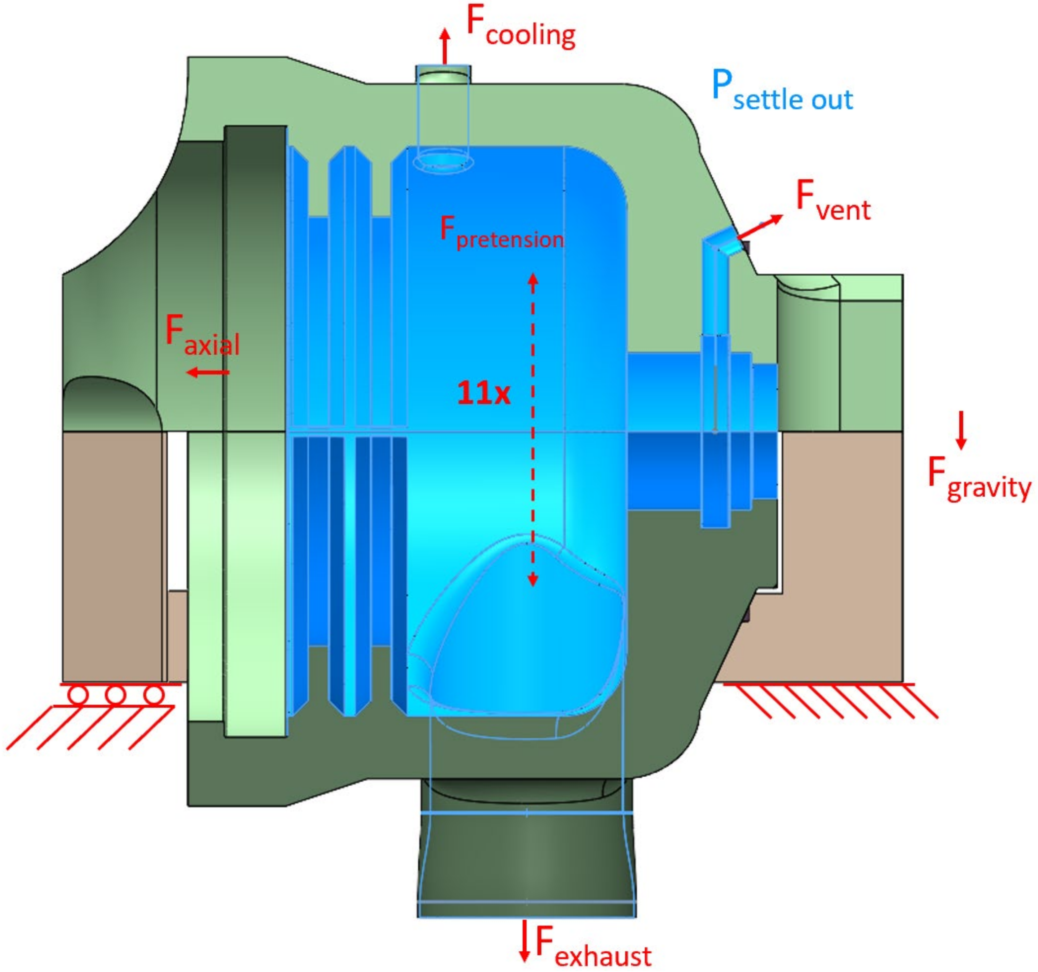
- Inner Case (315bar): Barrel case
- Outer Case (50bar≈settleout): Horizontally split
- 22X 5”x5’ (nut to nut) K14072 (1Cr-1/2Mo) bolts
- 1’-2’ thick case of J42045 (5Cr-1/2Mo)
- Twin 37” exhaust pipes (bottom)
- Twin 9.5” Cooling inlets (top)
- ~37” diffuser axial length
- 2.5’ tall flanges

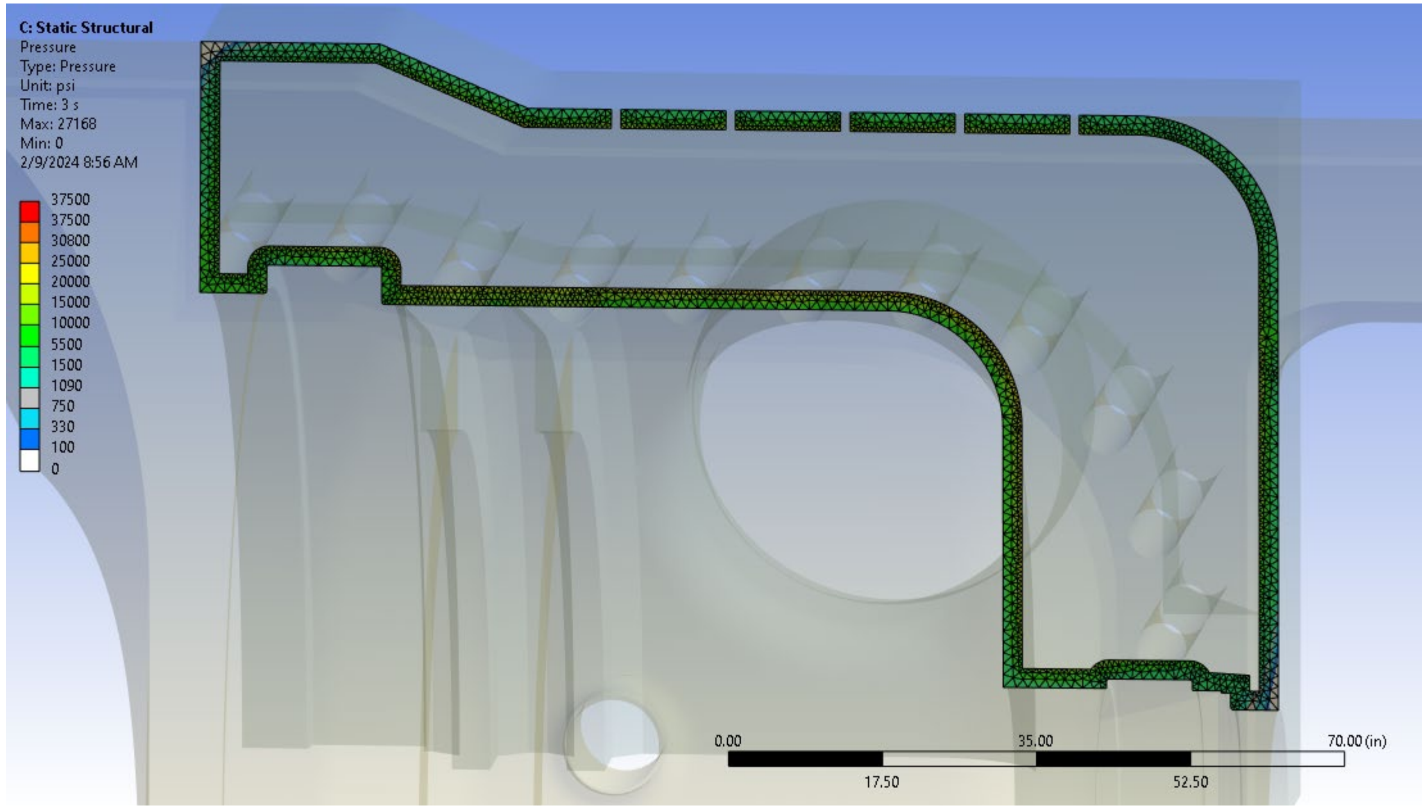






Case Design

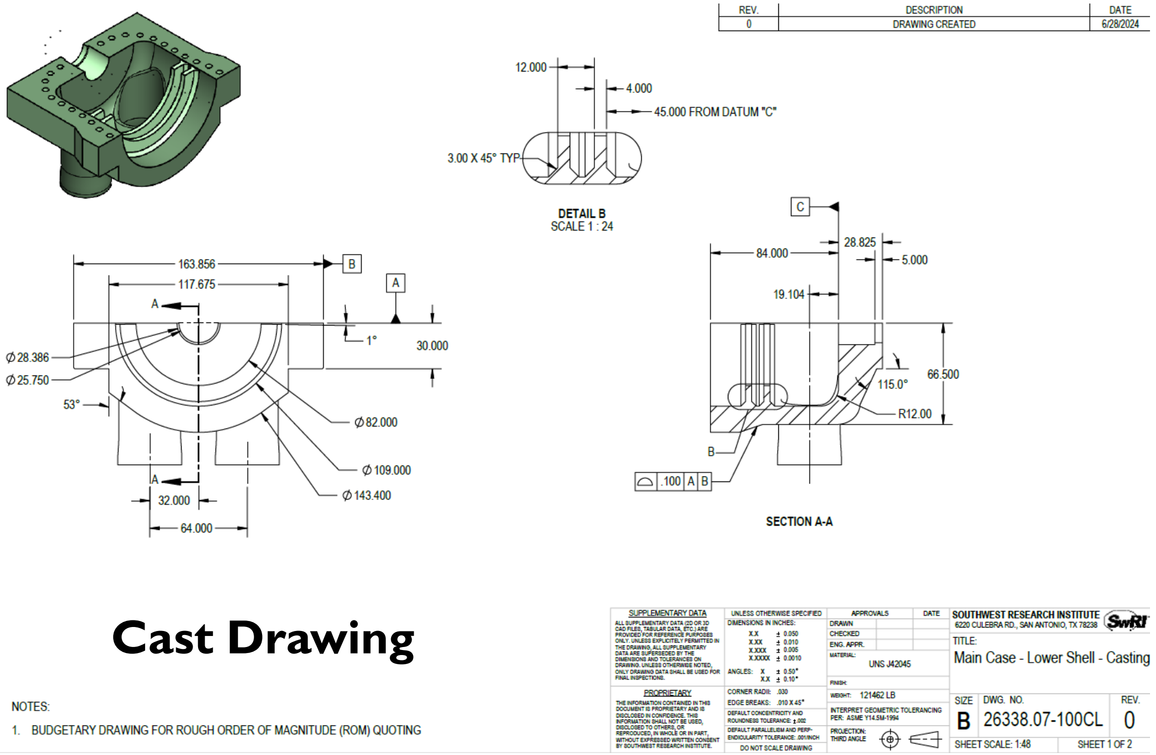



C: Static Structural
Pressure
Type: Pressure
Unit: psi
Time: 3 s
Max: 27168
Min: 0
2/9/2024 8:56 AM

	"Real" Load		"Design Margin" Load		"Limit Load" Load		"1/2 Model Limit Load" Load		
	Description	**Value**	**Factor**	**Value**	**Factor**	**Value**	**Factor**	**Value**	**Unit**
$F_{gravity}$	m·g	151	1	151	1.5	227	0.5	**113**	**kips**
$P_{settle\ out}$	49 bar_g	711	1.1	782	1.5	1,172	1	**1,172**	**psi**
$F_{pretension}$	75% * (2·Sa*$A\|_{OD=5",ID=0.625",8TPI}$)	780,371	1	780,371	1	780,371	1	**780,371**	**lbf**
$F_{exhaust}$	$P_{settleout}$ x ø 41"	938,041	1.1	1,031,845	1.5	1,547,767	1	**1,547,767**	**lbf**
$F_{cooling}$ inlet	$P_{settleout}$ x ø 9.562"	51,021	1.1	56,123	1.5	84,185	1	**84,185**	**lbf**
F_{vent}	$P_{settleout}$ x ø 7.765"	33,646	1.1	37,011	1.5	55,516	0.5	**27,758**	**lbf**
F_{axial}	$P_{settleout}$ x ($A\|_{ø\ 117"-26.25"}$)/2	7,254,295	1.1	7,979,725	1.5	11,969,587	0.5	**5,984,794**	**lbf**

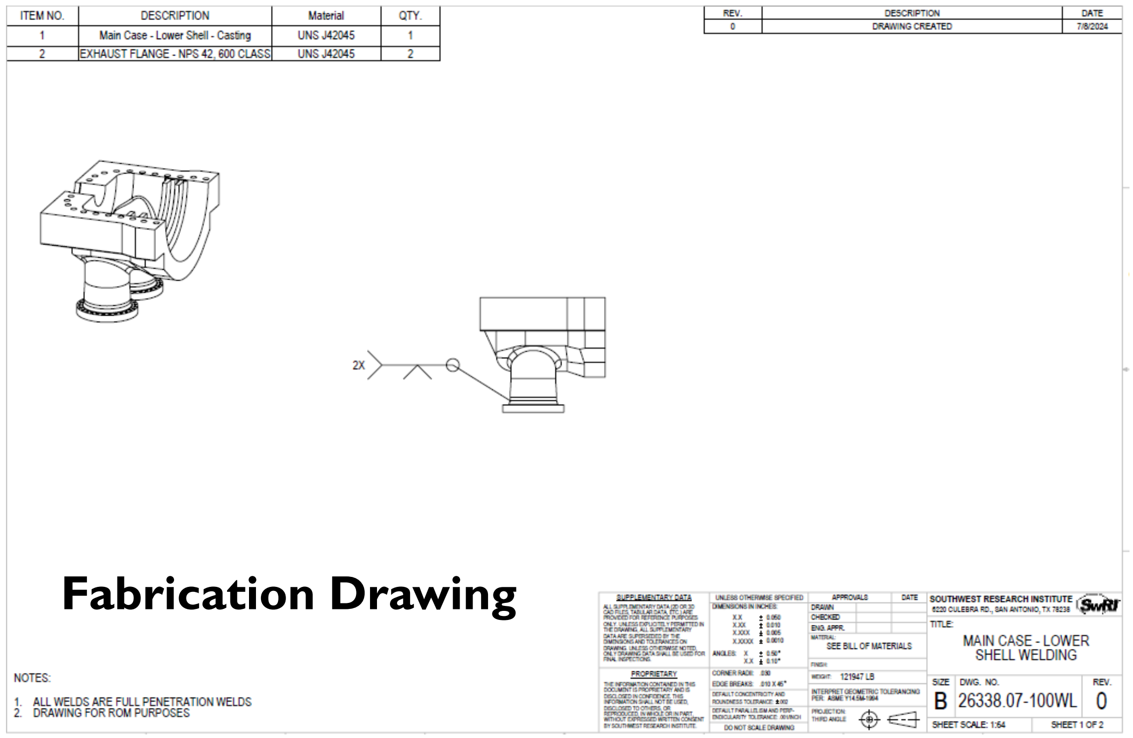
- FEA at nominal loads used to verify sealing pressure is maintained for split case.
- Limit load analysis converged according to BPVC Section VIII, Div. 2.

Case – Manufacturing Process



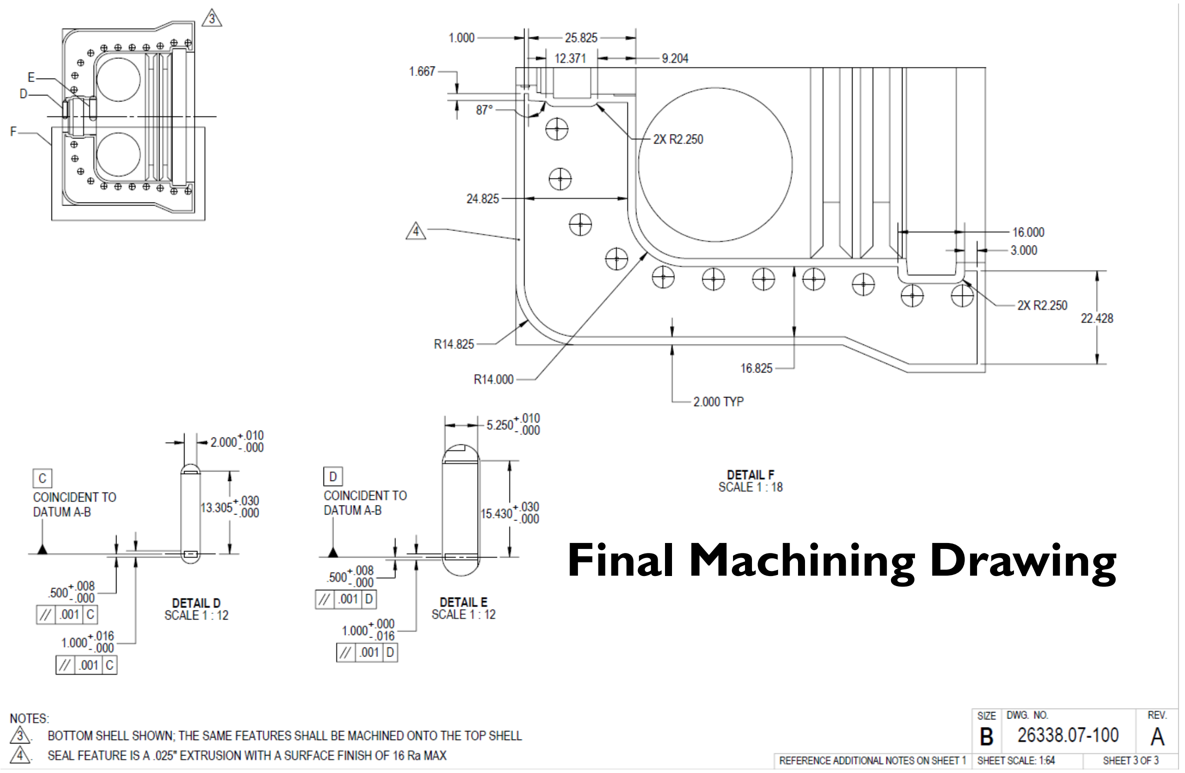
Cast Drawing

NOTES:
1. BUDGETARY DRAWING FOR ROUGH ORDER OF MAGNITUDE (ROM) QUOTING



Fabrication Drawing

NOTES:
1. ALL WELDS ARE FULL PENETRATION WELDS
2. DRAWING FOR ROM PURPOSES

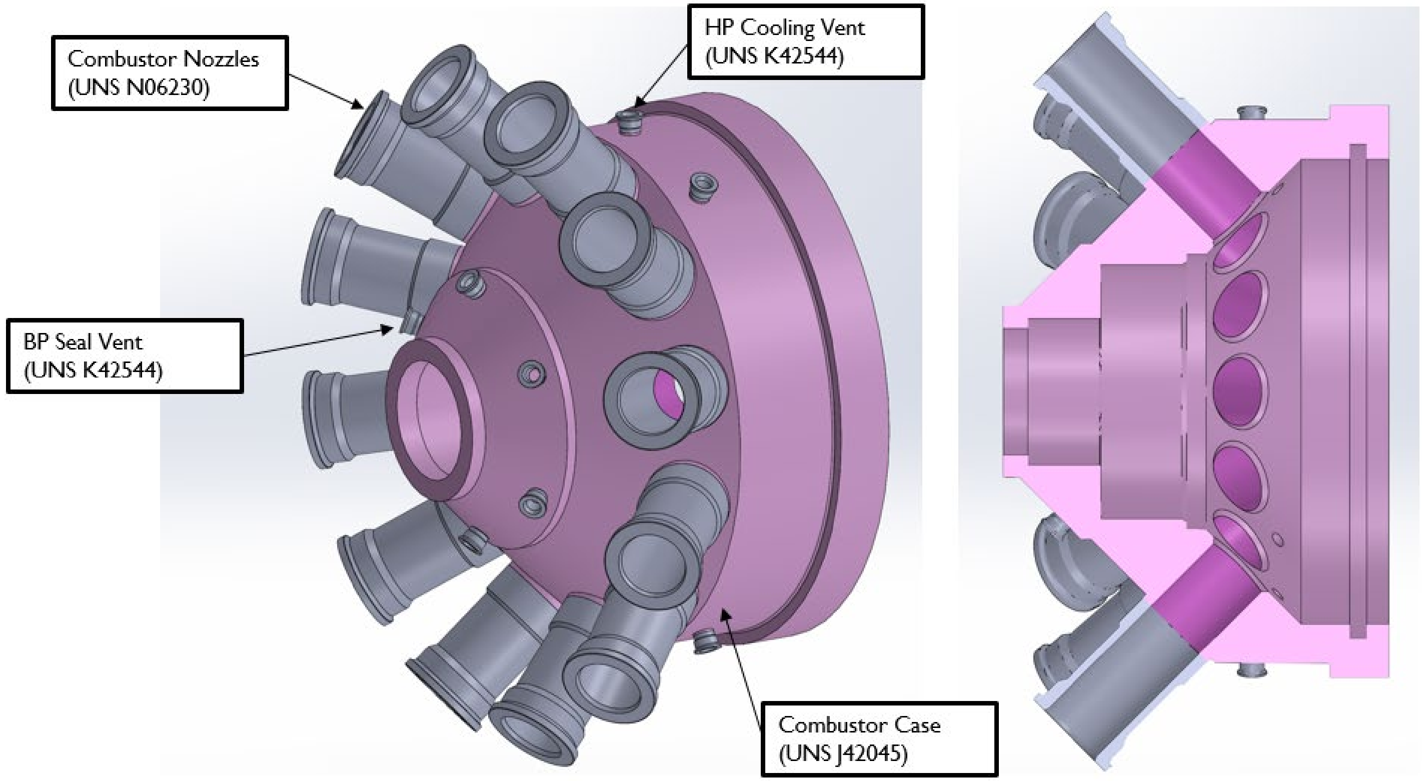


Final Machining Drawing

NOTES:
3. BOTTOM SHELL SHOWN; THE SAME FEATURES SHALL BE MACHINED ONTO THE TOP SHELL
4. SEAL FEATURE IS A .025" EXTRUSION WITH A SURFACE FINISH OF 16 Ra MAX

- Turbine case manufacturing process includes casting, welding, and final machining.
- Engineering drawings include sealing surfaces and keyway features.

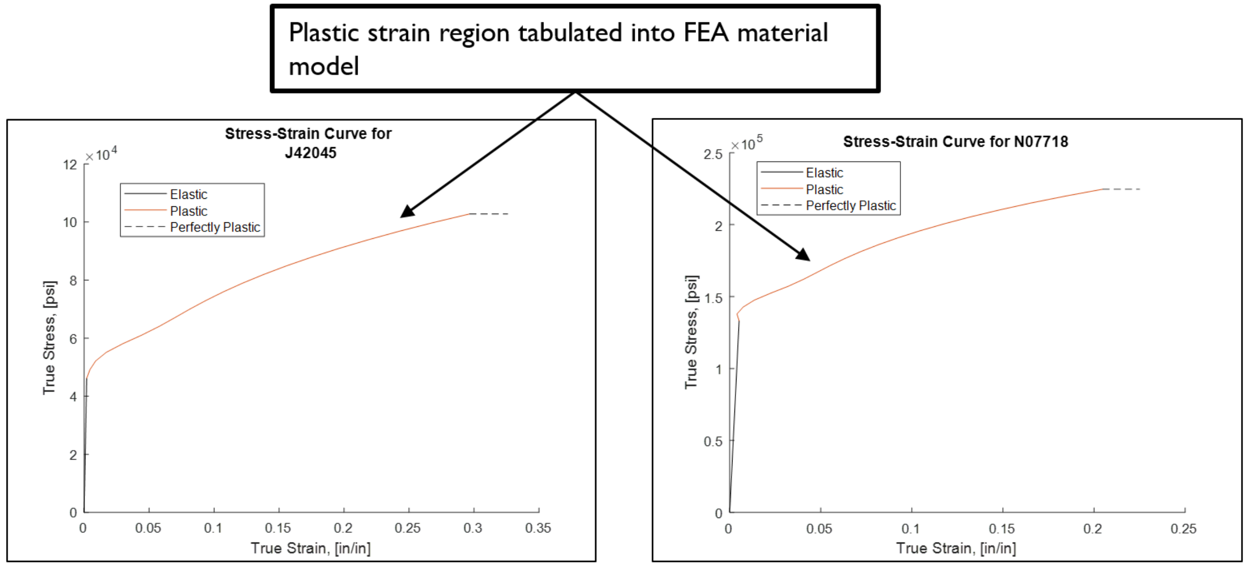
Combustor Housing Design

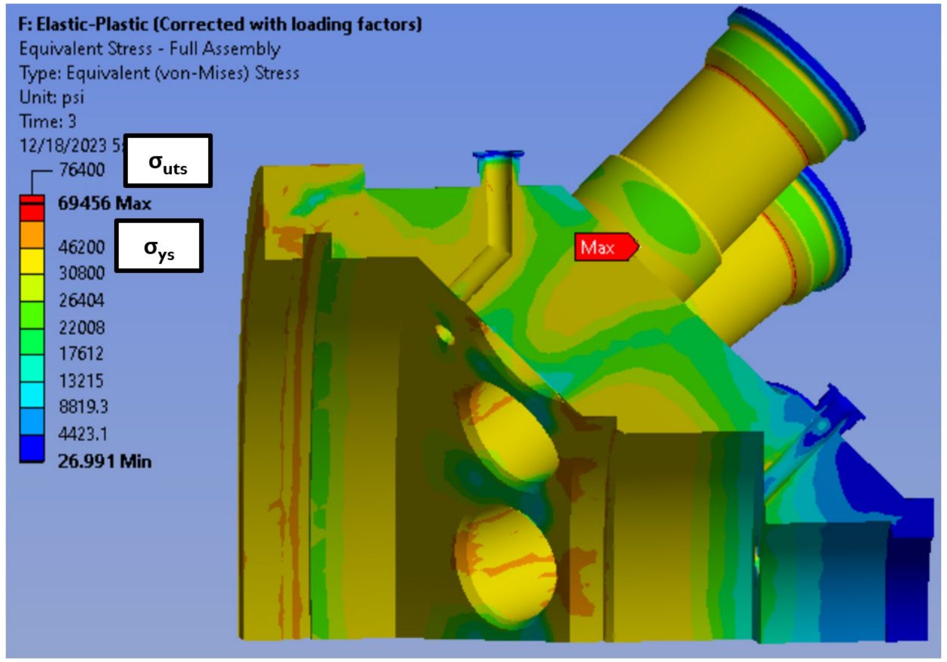

Combustor Nozzles (UNS N06230)

HP Cooling Vent (UNS K42544)

BP Seal Vent (UNS K42544)

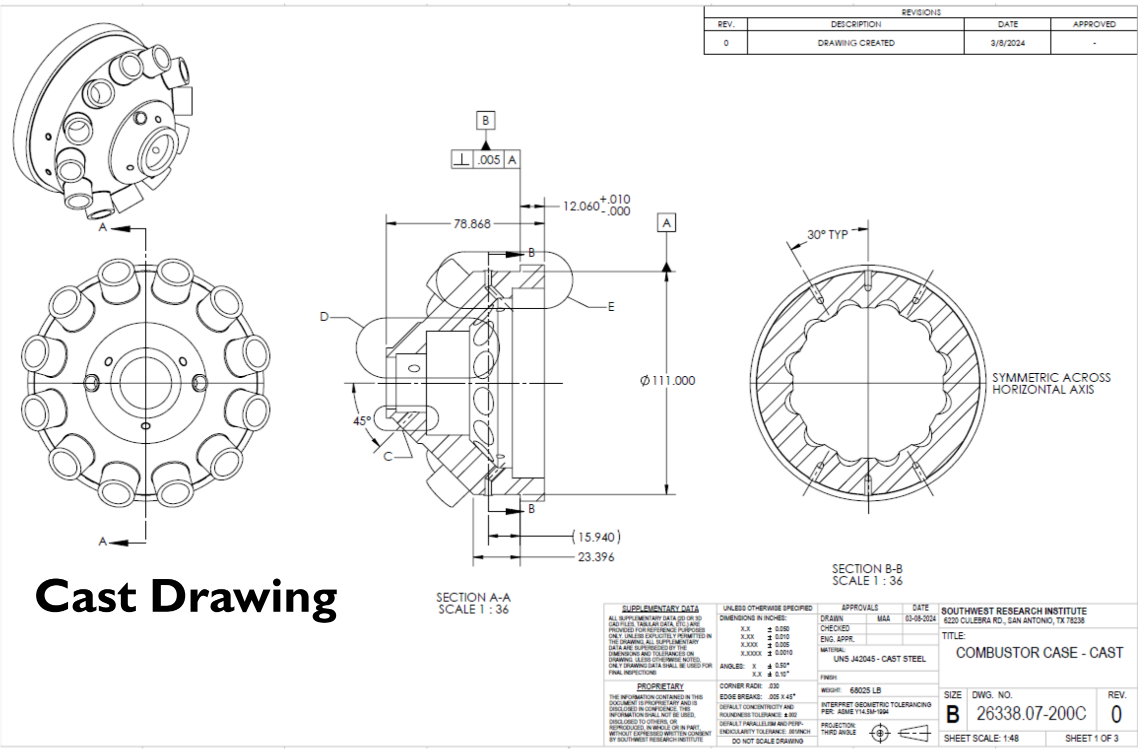
Combustor Case (UNS J42045)

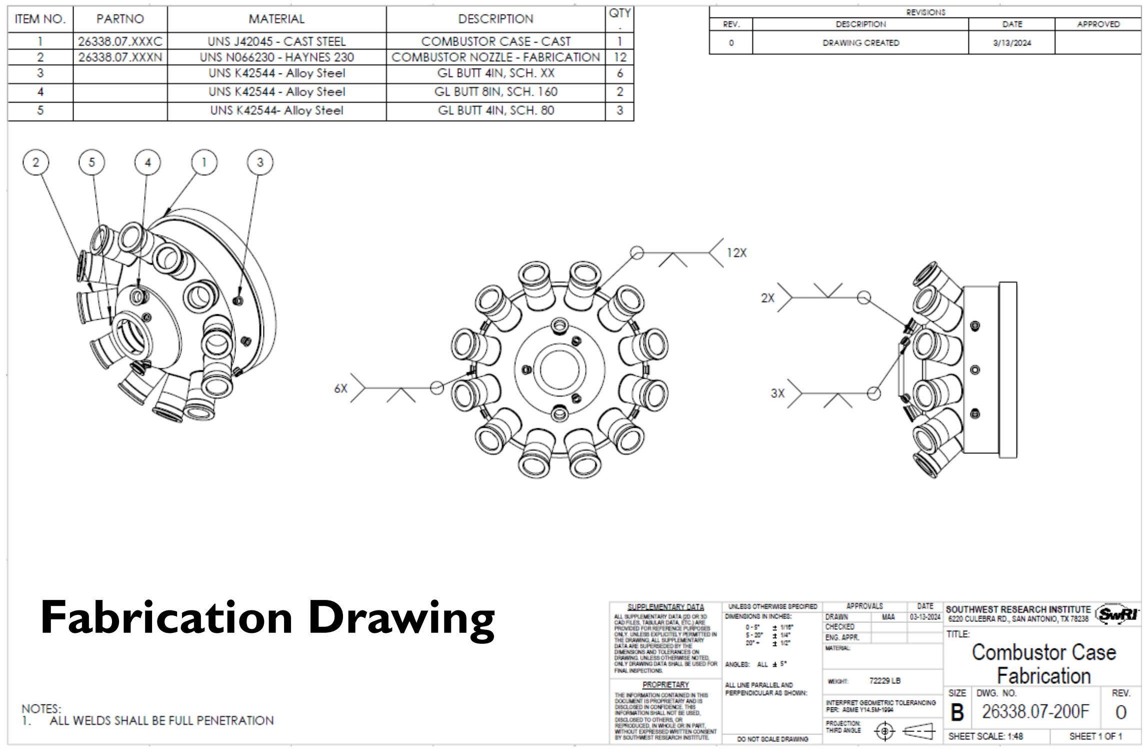

Plastic strain region tabulated into FEA material model



- Combustor housing materials include high-strength cast steels (J42045), with Haynes 230 used for combustor nozzles due to localized high temperature region.
- Limit load and local failure analyses completed and converged according to Section VIII, Div. 2.

Combustor Housing – Manufacturing Process

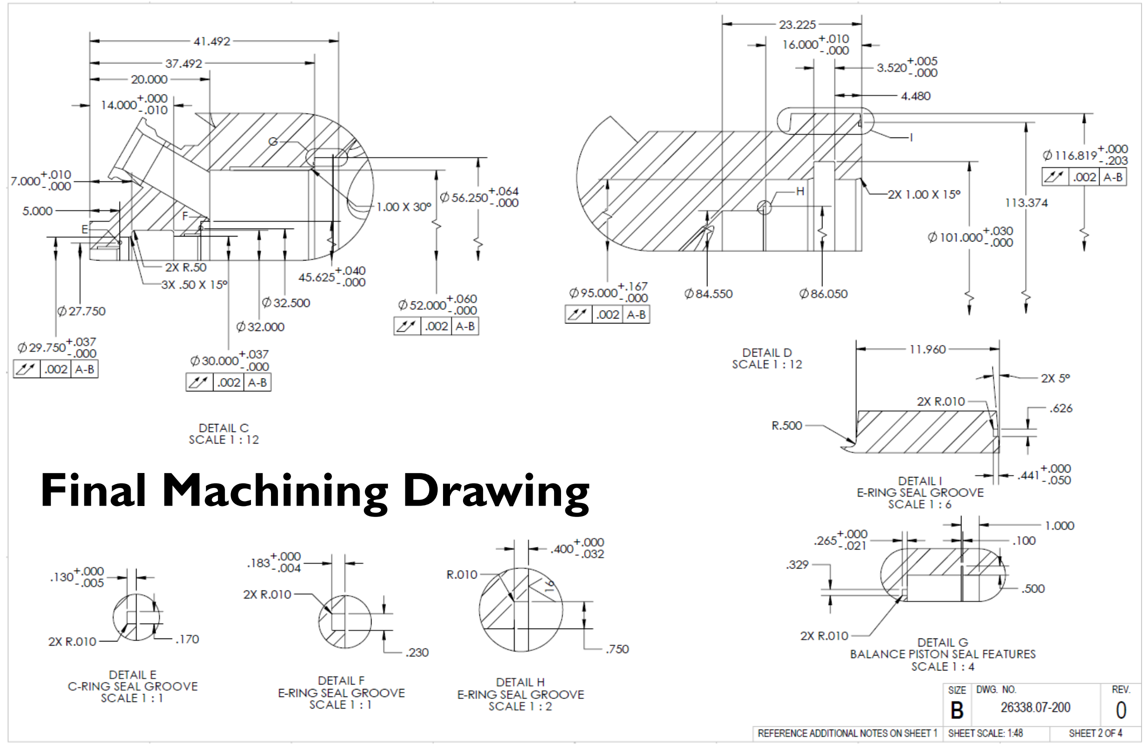

Cast Drawing


Fabrication Drawing

ITEM NO.	PARTNO	MATERIAL	DESCRIPTION	QTY.
1	26338.07.XXXC	UNS J42045 - CAST STEEL	COMBUSTOR CASE - CAST	1
2	26338.07.XXXN	UNS N066230 - HAYNES 230	COMBUSTOR NOZZLE - FABRICATION	12
3		UNS K42544 - Alloy Steel	GL BUTT 4IN, SCH. XX	6
4		UNS K42544 - Alloy Steel	GL BUTT 8IN, SCH. 160	2
5		UNS K42544- Alloy Steel	GL BUTT 4IN, SCH. 80	3

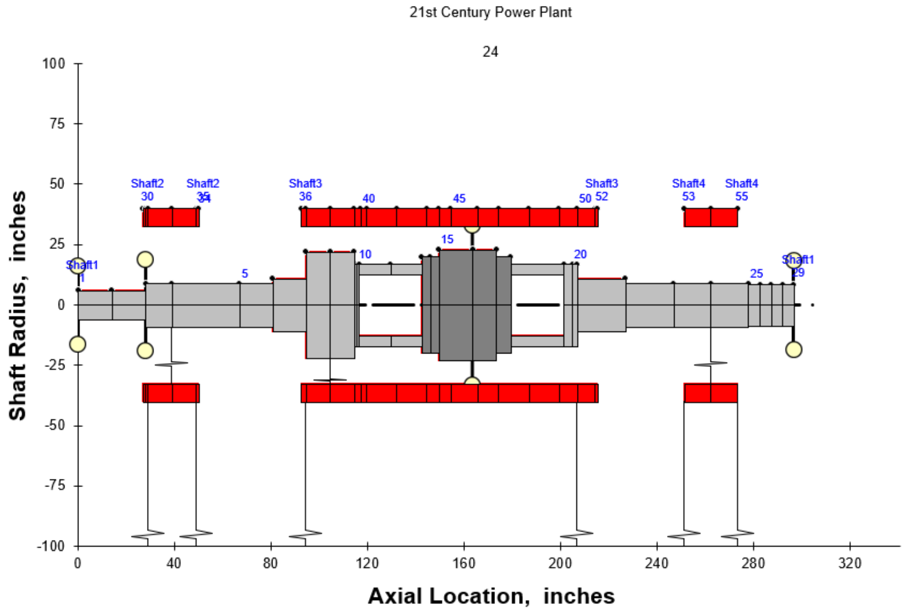
NOTES:
1. ALL WELDS SHALL BE FULL PENETRATION

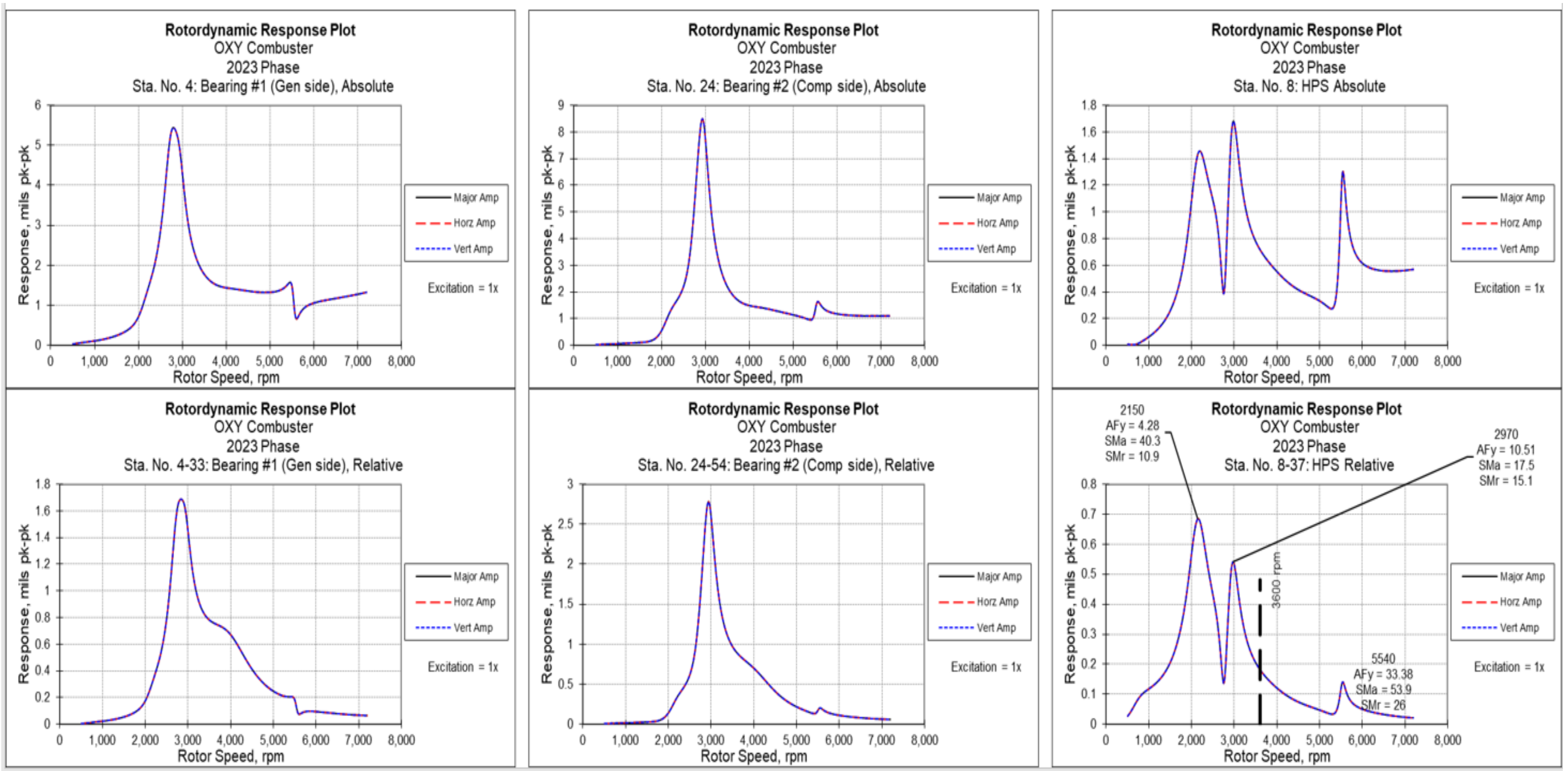
- Combustor housing manufacturing process includes casting, welding, and final machining.
- Engineering drawings include sealing surfaces and keyway features.


Final Machining Drawing

Rotordynamic Review

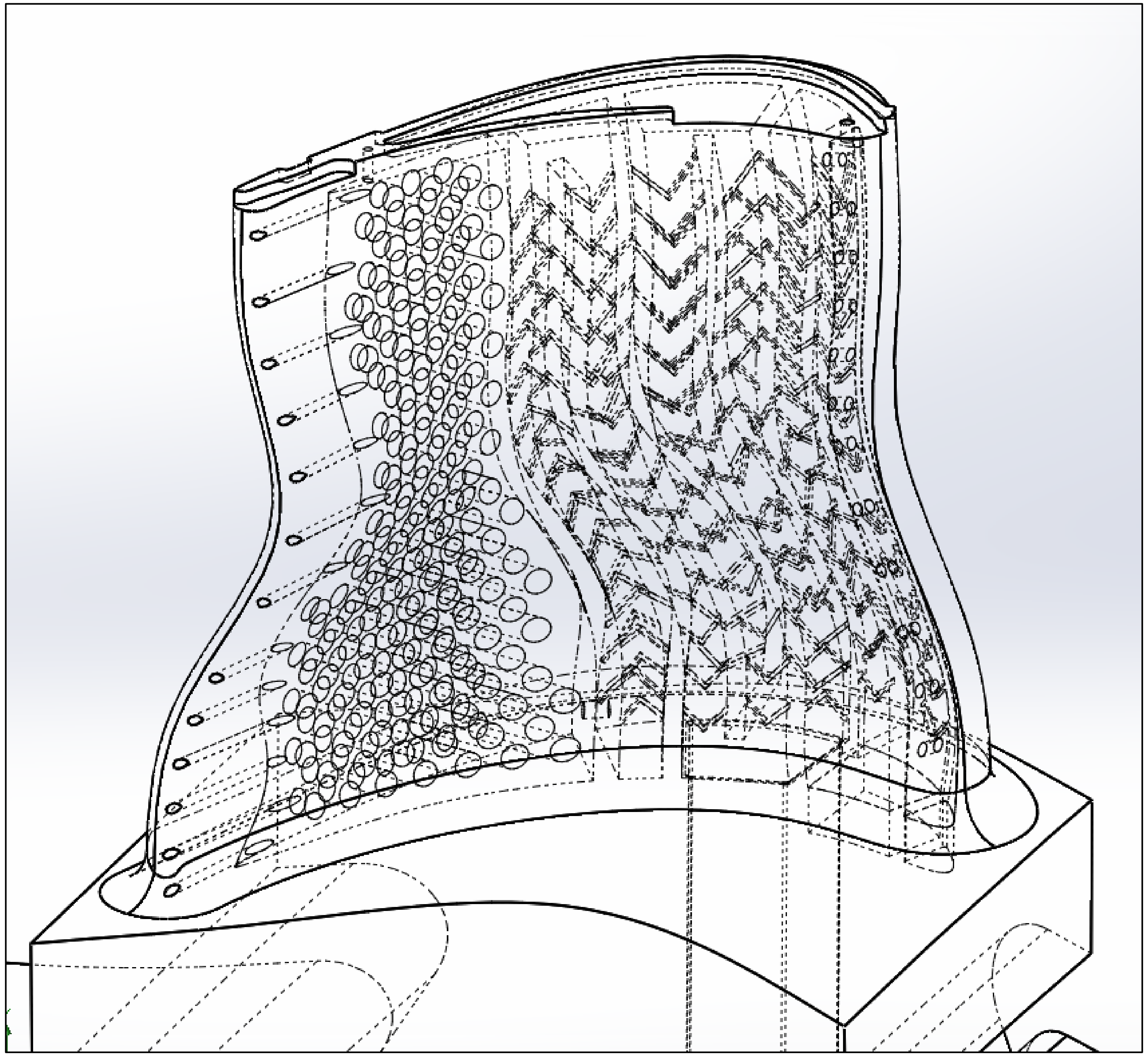
- Lateral Rotordynamic predictions show acceptable vibration response per API including
  - Balance piston seal active (steady state operation)
  - Balance piston seal inactive (start-up)
  - Range of imbalance conditions
  - Range of possible bearing dynamic coefficient measurements
- Housing stiffness and connection to ground are important factors.



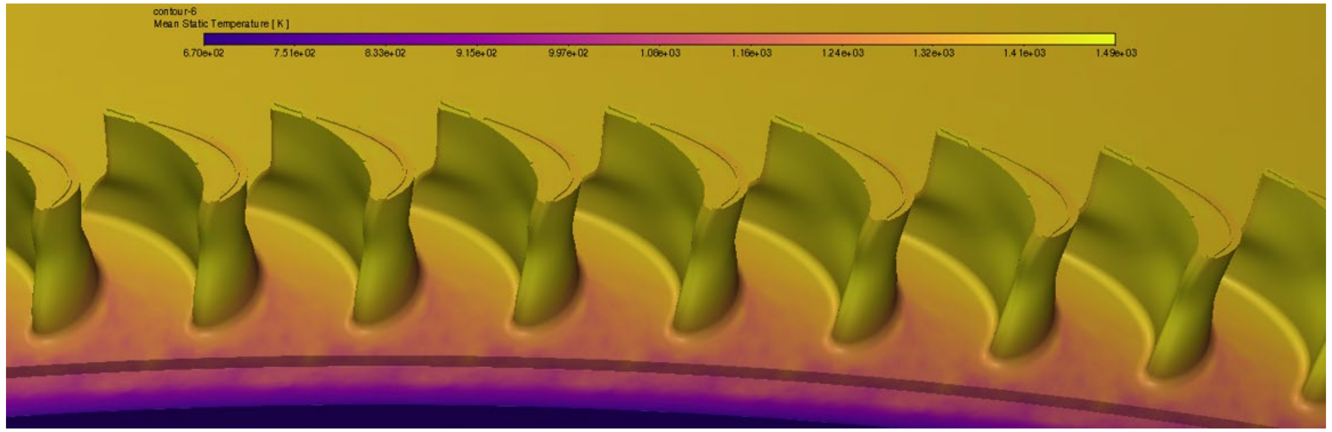


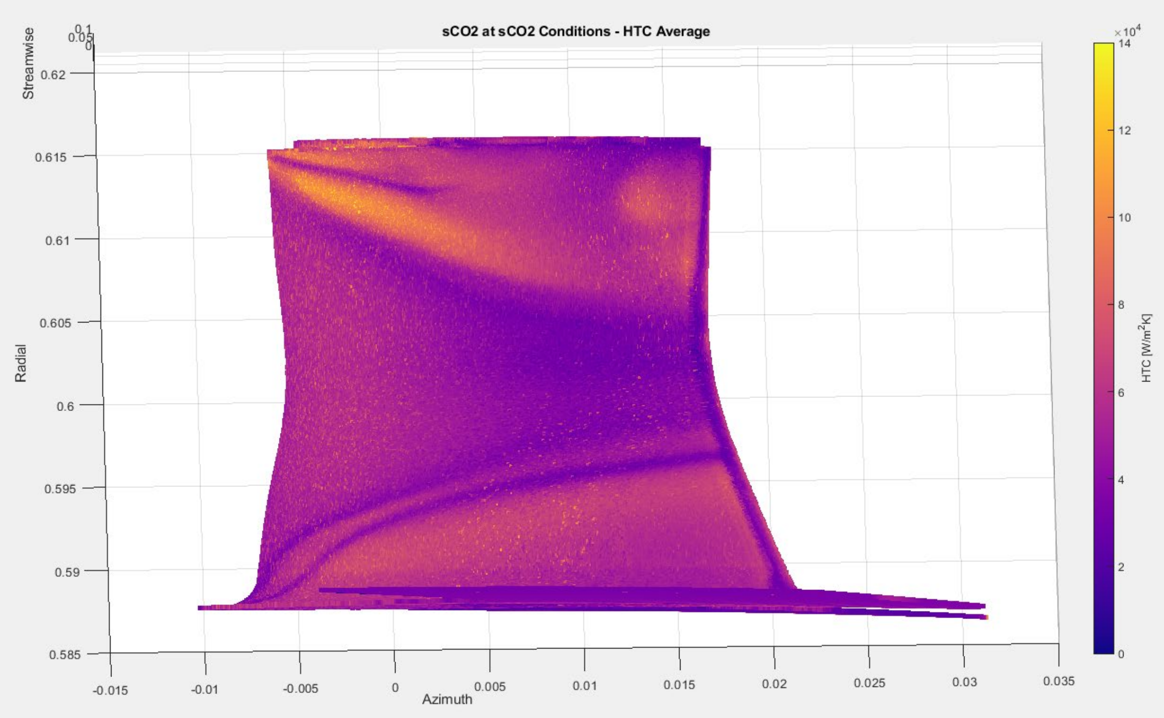
S1B Internal Cooling Design

- Leading edge impingement
- Ribbed serpentine channels
- Pin-fin array
- Trailing edge ejection
- Thermal Barrier Coating

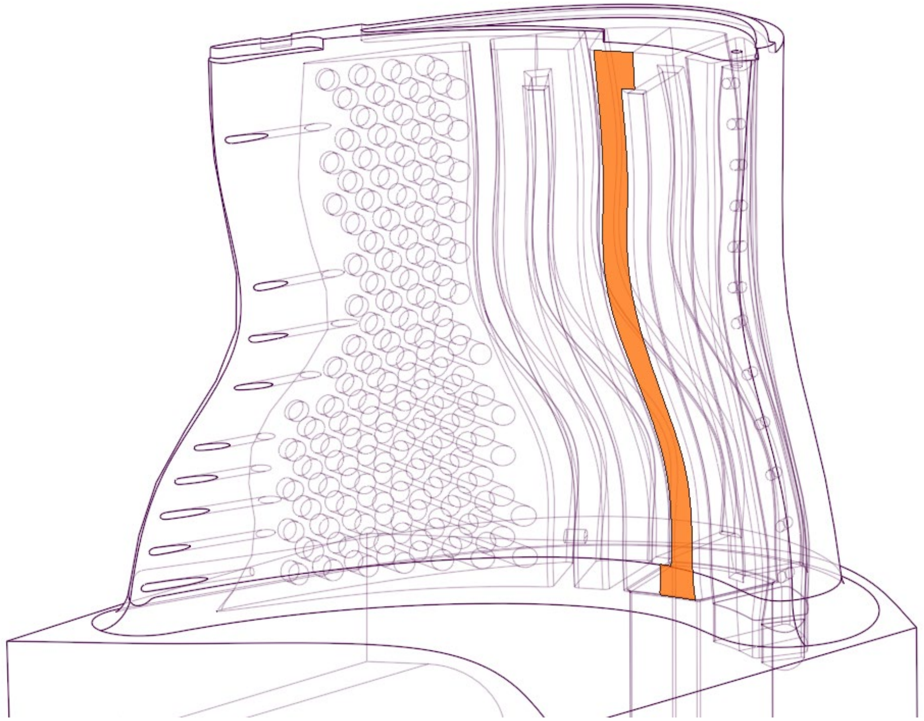


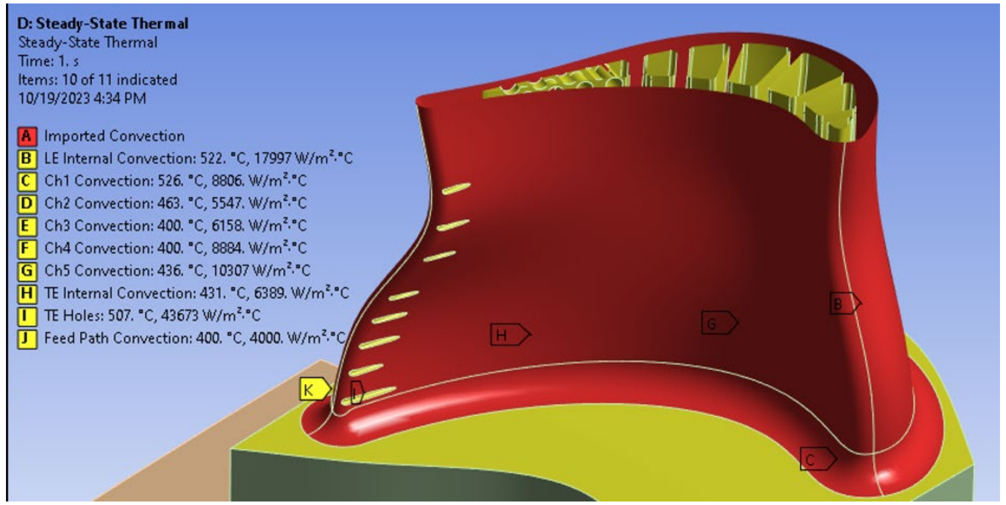
S1B – External Heat Loads





Purdue unsteady CFD conducted in 2024 includes S1N-S1B cavity purge cooling flow and combustor outlet flow non-uniformity effects.





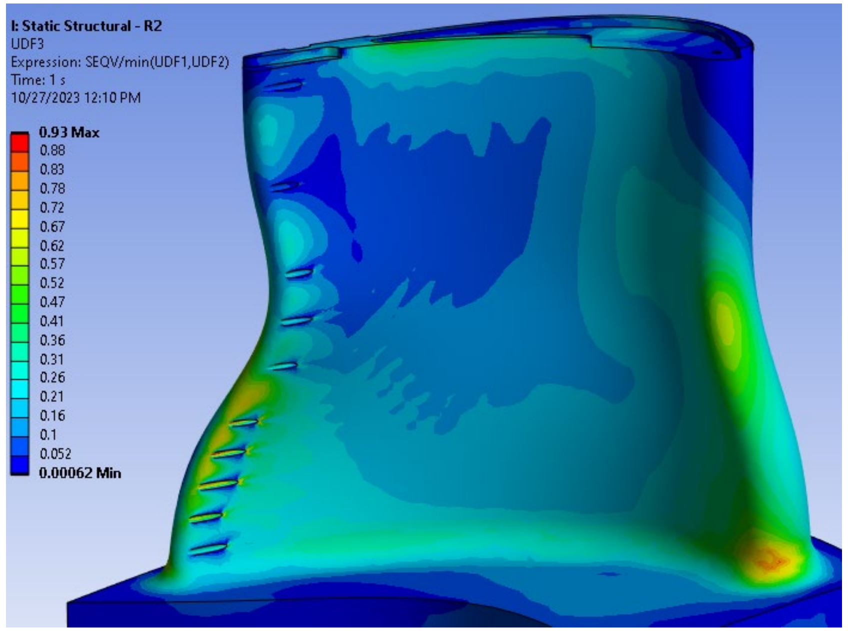
D: Steady-State Thermal
Steady-State Thermal
Time: 1. s
Items: 10 of 11 indicated
10/19/2023 4:34 PM

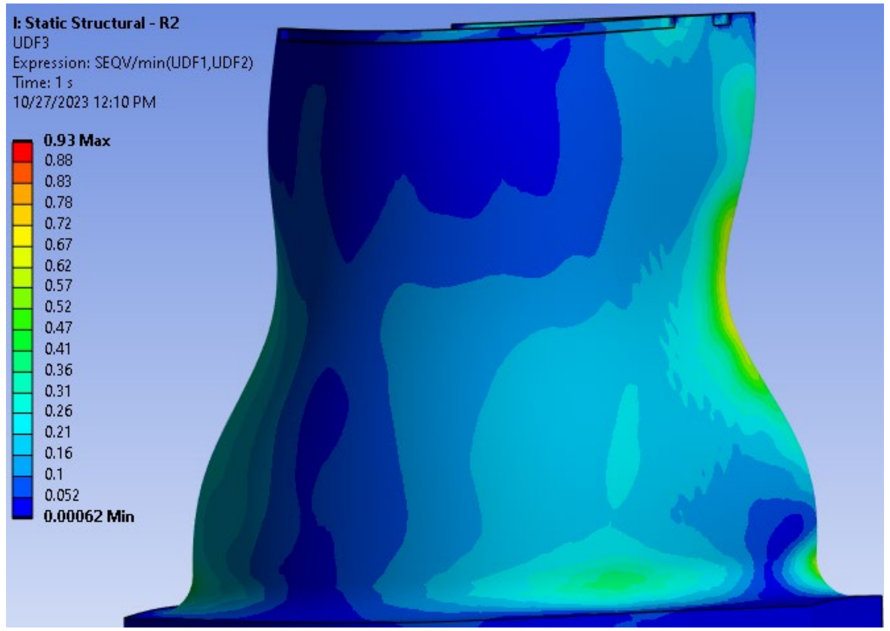
A Imported Convection
B LE Internal Convection: 522. °C, 17997 W/m²·°C
C Ch1 Convection: 526. °C, 8806. W/m²·°C
D Ch2 Convection: 463. °C, 5547. W/m²·°C
E Ch3 Convection: 400. °C, 6158. W/m²·°C
F Ch4 Convection: 400. °C, 8884. W/m²·°C
G Ch5 Convection: 436. °C, 10307 W/m²·°C
H TE Internal Convection: 431. °C, 6389. W/m²·°C
I TE Holes: 507. °C, 43673 W/m²·°C
J Feed Path Convection: 400. °C, 4000. W/m²·°C

FE model imports external heat load on blade and platform, while applying internal heat transfer correlations locally.

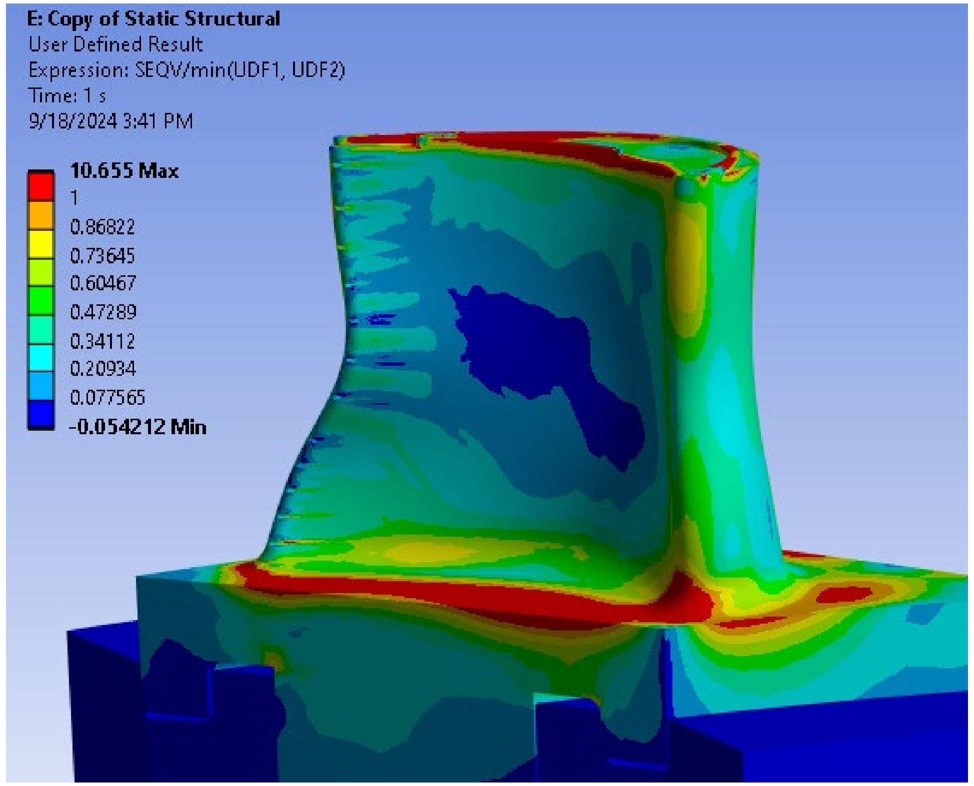
SIB FEA Result

$$f = \frac{\sigma_{VM}}{\min(UTS(T),\sigma_{cr}(T))}$$





- 2023: Pressure loading, centrifugal loading applied.
- Assumes Haynes 282 creep properties



- 2024: Pressure loading, centrifugal loading, thermal expansion effects with updated geometry and unsteady CFD for more accurate external load.
- Localized regions remain with function value over 1, signifying life prediction < 30k hrs.
- Final iterations being completed to achieve 30k hr. life.
- Validation of testing will take place in 2024/2025 at SwRI facility reusing existing BP2 test rig.

Cost estimation for TEA update

- To generate cost estimates the following RFQs have been sent to over 19 vendors:
  - Main Case (75 ton upper shell, 61 ton lower shell): *Casting, welding and final machining.*
  - Combustor Case (37 tons): *Casting, welding and final machining.*
  - Inner Case (12 tons): *Forging, final machining.*
- The casting size was too heavy for a majority of facilities, Goodwin Steel Castings and Voest Alpine were two vendors who had sufficient capacity and provided budgetary quotes.

Cost estimation for TEA update

- Sub-component costs have been estimated based on historical cost data and factoring for size differences.
- Main remaining costs are the final machining budgetary quotes, turbine rotor, and blades/stators.

Component / Category	**Total Component / Category Cost**
DE Labyrinth Seal	$ 29,604
NDE Labyrinth Seal	$ 29,604
Balance Piston Seal	$ 151,990
Metallic Seals, Rings, and Retainers	$ 40,962
Alignment Keys	$ 6,452
Grayloc Materials	$ 3,045,635
ANSI Flange Materials	$ 10,699
Superbolt Materials	$ 142,743
Main Case [CASTING]	$ 1,477,862
Combustor Case [CASTING]	$ 634,475
Inner Case [FINAL MACHINED]	$ 529,000
Exhaust Diffuser [FINAL CASTING]	$ 95,195
Turbine Rotor	
Combustor Liners	$ 561,600
Turbine Stator Block	$ 15,127,318
Turbine Blades and Stators	$ -
Total ($ Million)	*$ 21.9*

Publications

- Logan Tuite, Purdue University, presented at the 2024 sCO_2 Symposium in San Antonio: *Paper 102 Blade and Rim Seal Design of a First Stage High Pressure Turbine for a 300 MWe Supercritical CO2 Power Cycle.*
- Michael Marshall, Southwest Research Institute, presented at the 2024 sCO_2 Symposium in San Antonio: *Paper 67 Heat Transfer Experiments of Ribbed, Serpentine Cooling Passages with Supercritical* CO_2.
- Logan Tuite, Purdue University, presented at the 2023 ASME Turbo Expo in Boston, Massachusetts: *GT2023-101722, Optimization of an HPT Blade and Sector-Based Annular Rig Design for Supercritical CO2 Power Cycle Representative Testing.*
- Ryan Wardell, University of Central Florida, presented at the 2023 ASME Turbo Expo in Boston, Massachusetts: *GT2023-103263, An Experimental Investigation of Heat Transfer for Supercritical Carbon Dioxide Cooling in a Staggered Pin Fin Array.*
- John Richardson, University of Central Florida, presented at the 2023 ASME Turbo Expo in Boston, Massachusetts: *GT2023-102544, Experimental & Computational Heat Transfer Study of* sCO_2 *Single Jet Impingement.*
- Jeff Moore, Southwest Research Institute, presented at the 2023 ASME Turbo Expo in Boston, Massachusetts: *GT2023-103328, Development of a 300 MWe Utility Scale Oxy-Fuel* sCO_2 *Turbine.*

Questions?