DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

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

FECM – Spring Project Review Meeting

DE-FE0031929

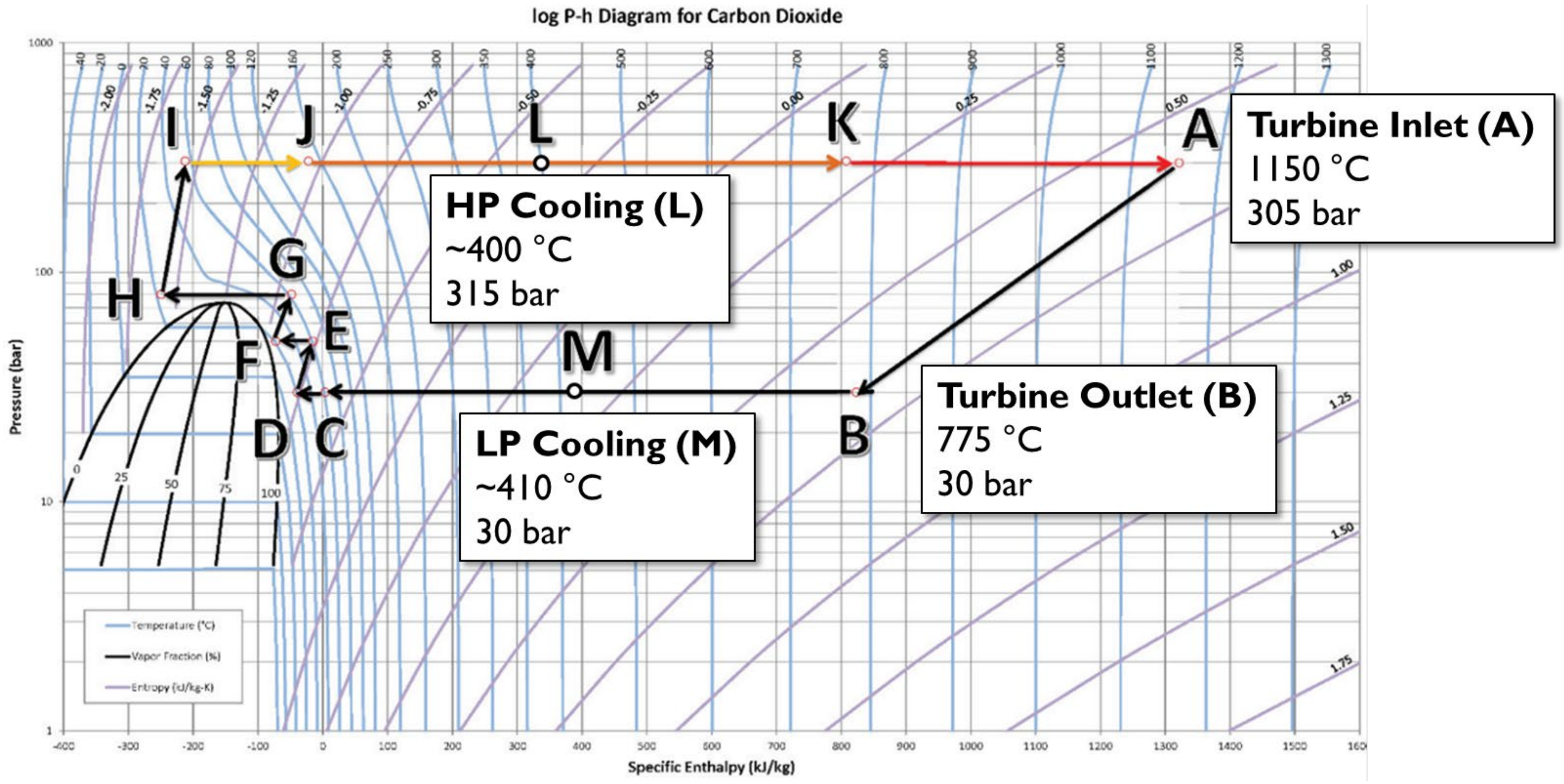
April 23-25, 2024

SwRI 8 RIVERS Air Liquide GE EPRI P UCF

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) 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.

Turbine Conditions



Turbine Inlet (A)
1150 °C
305 bar

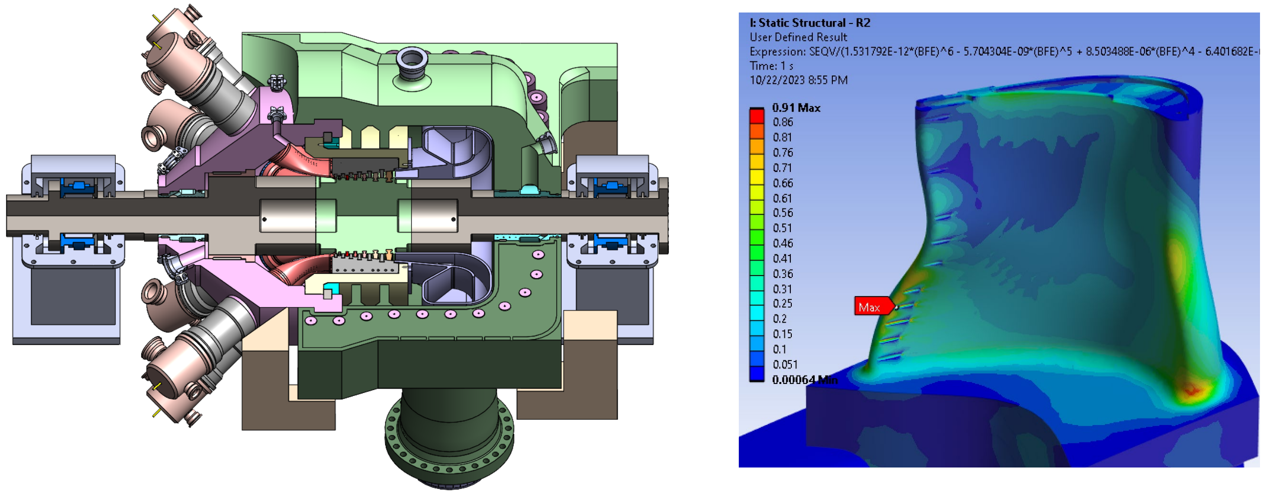
HP Cooling (L)
~400 °C
315 bar

LP Cooling (M)
~410 °C
30 bar

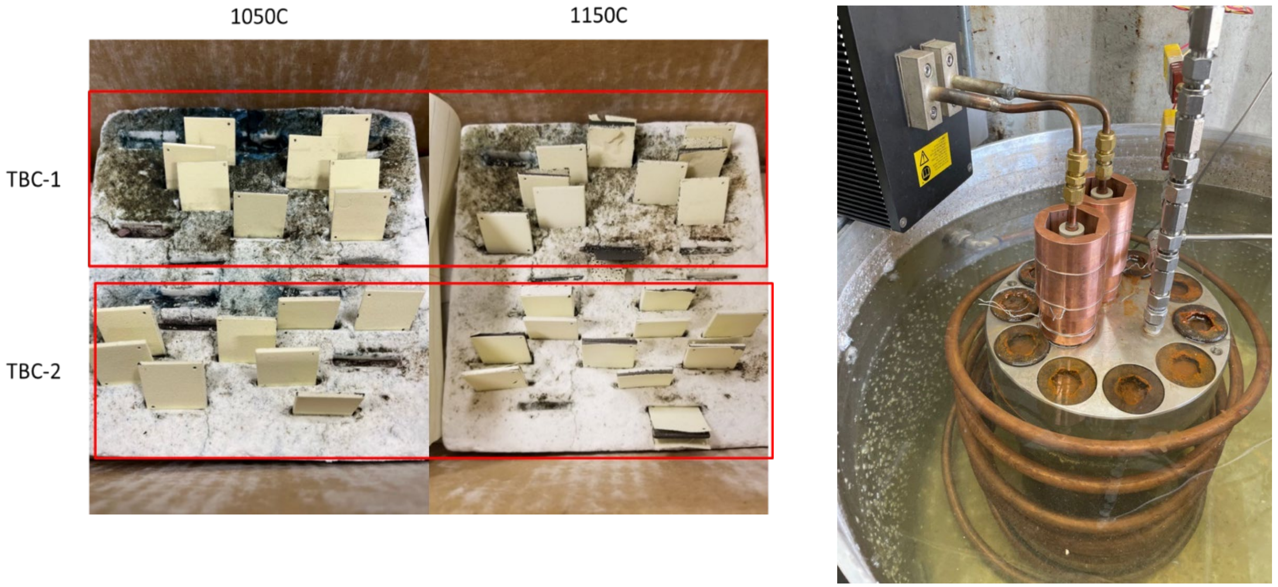
Turbine Outlet (B)
775 °C
30 bar

- 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)

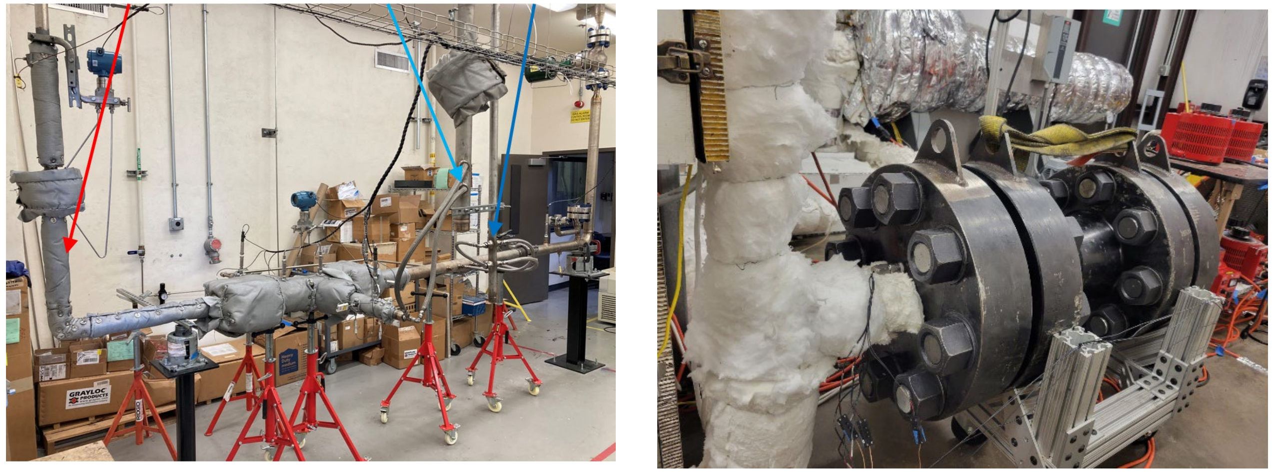
Project Components



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.

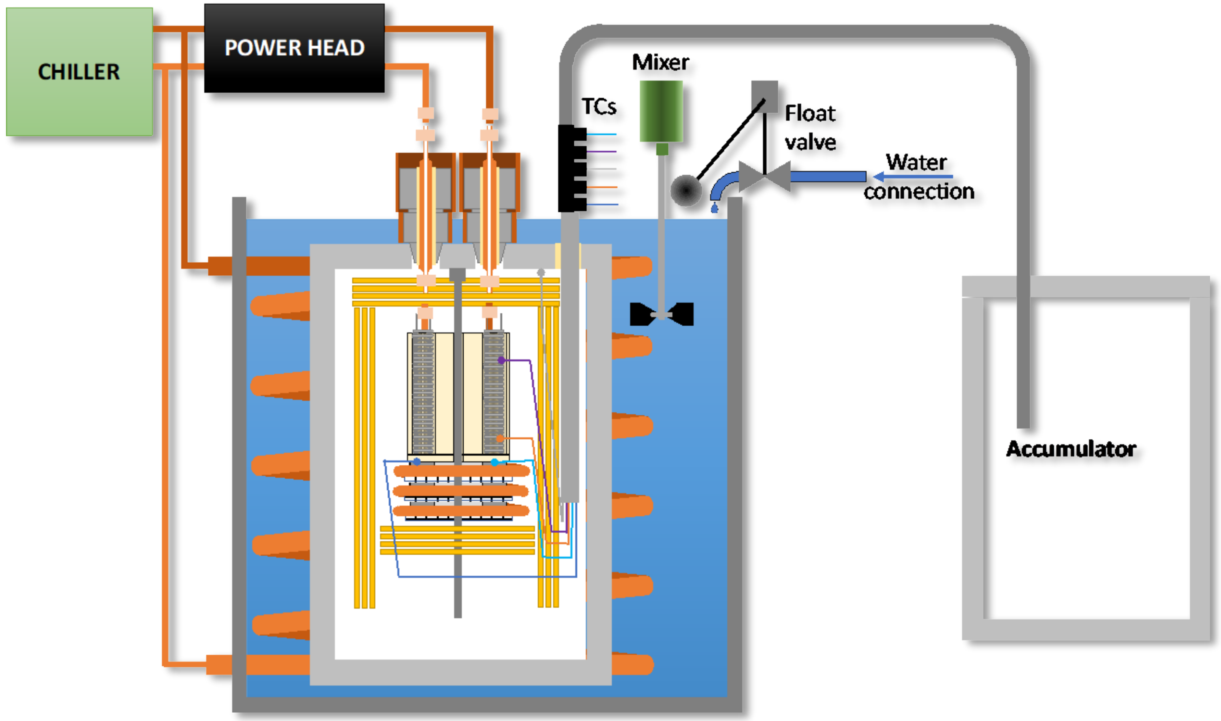
8 Rivers: Thermodynamic cycle model.

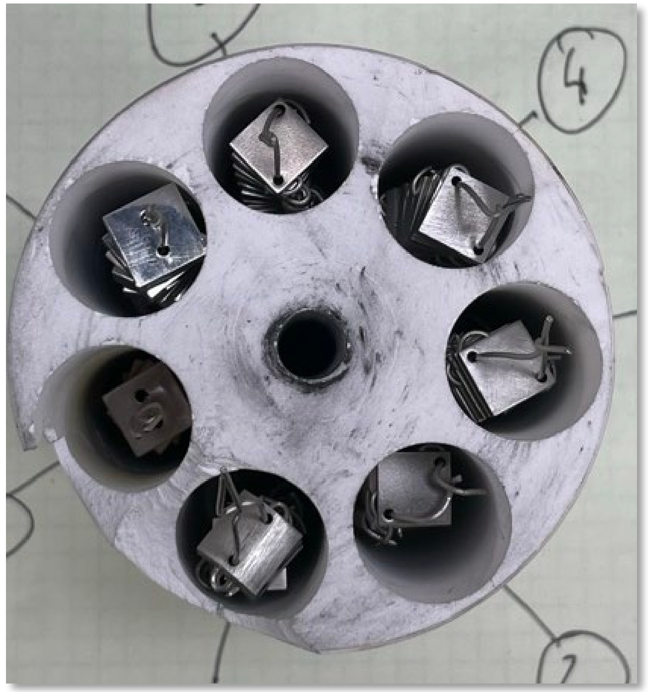
EPRI: Technoeconomic study.

Air Liquide: Oxy-combustor development.

Materials Testing

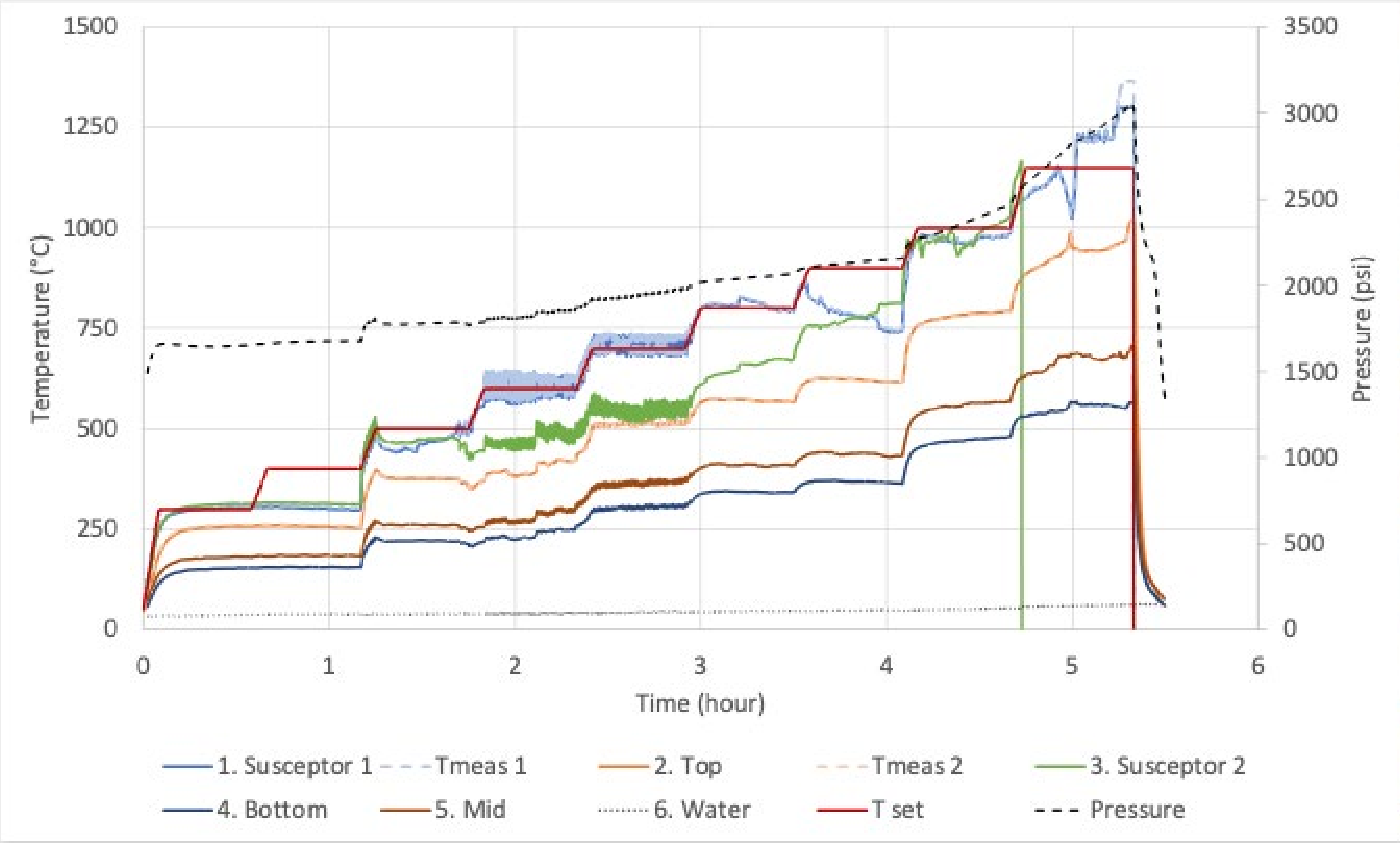
Autoclave Material Testing

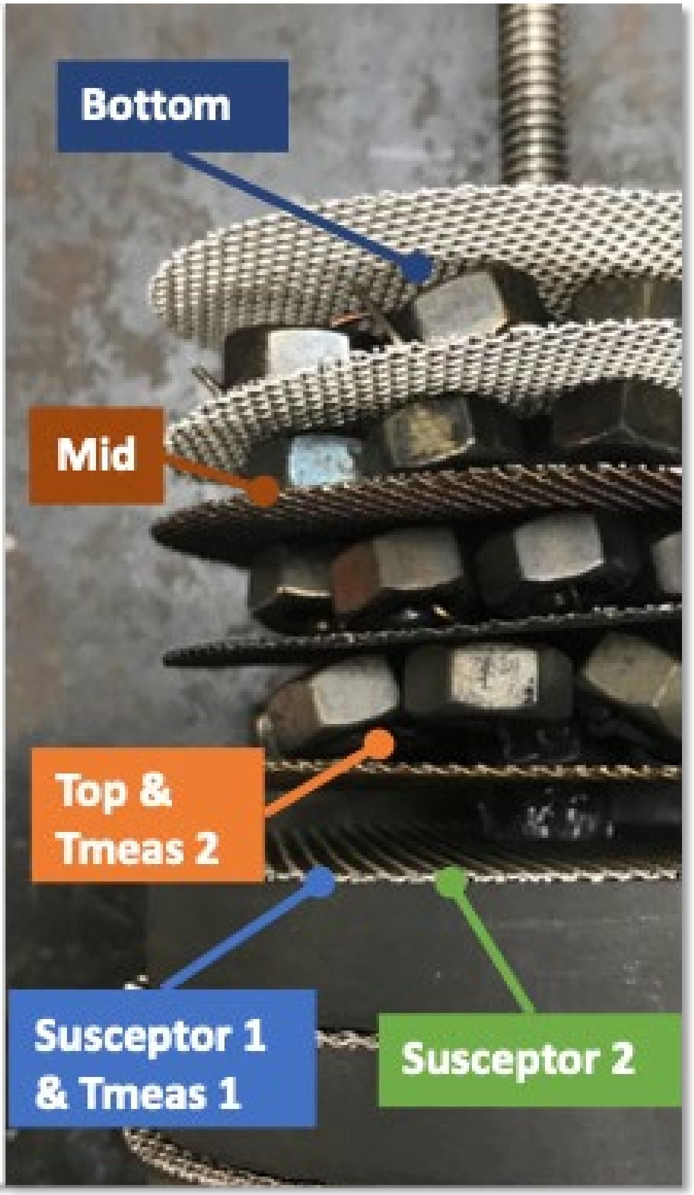




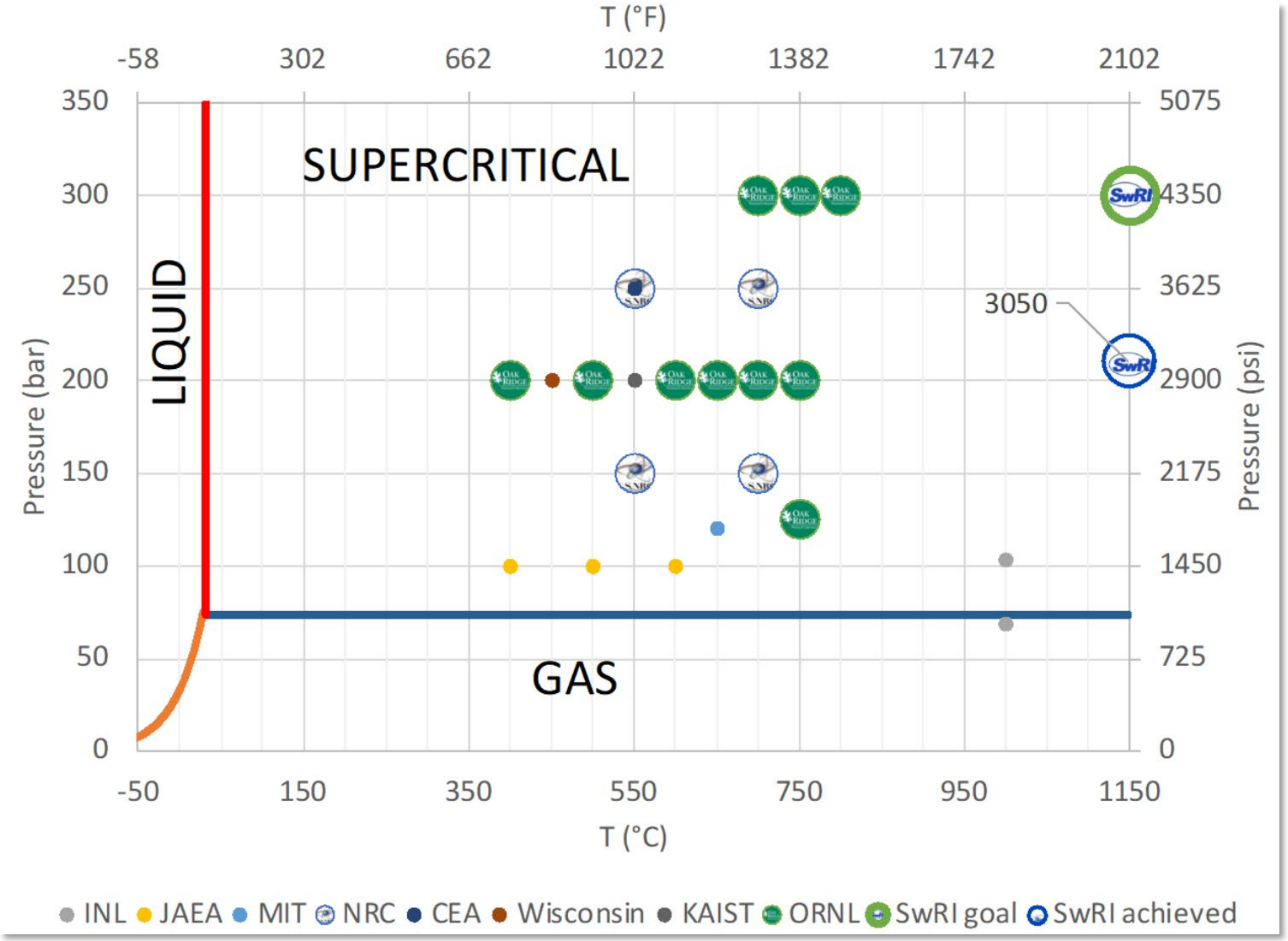
- Autoclave tests are for material and coatings exposure and oxidation characteristics observation at turbine inlet conditions.
- An induction heater with susceptor is used with TCs inserted to measure temperature throughout stack of material samples.

Autoclave Commissioning



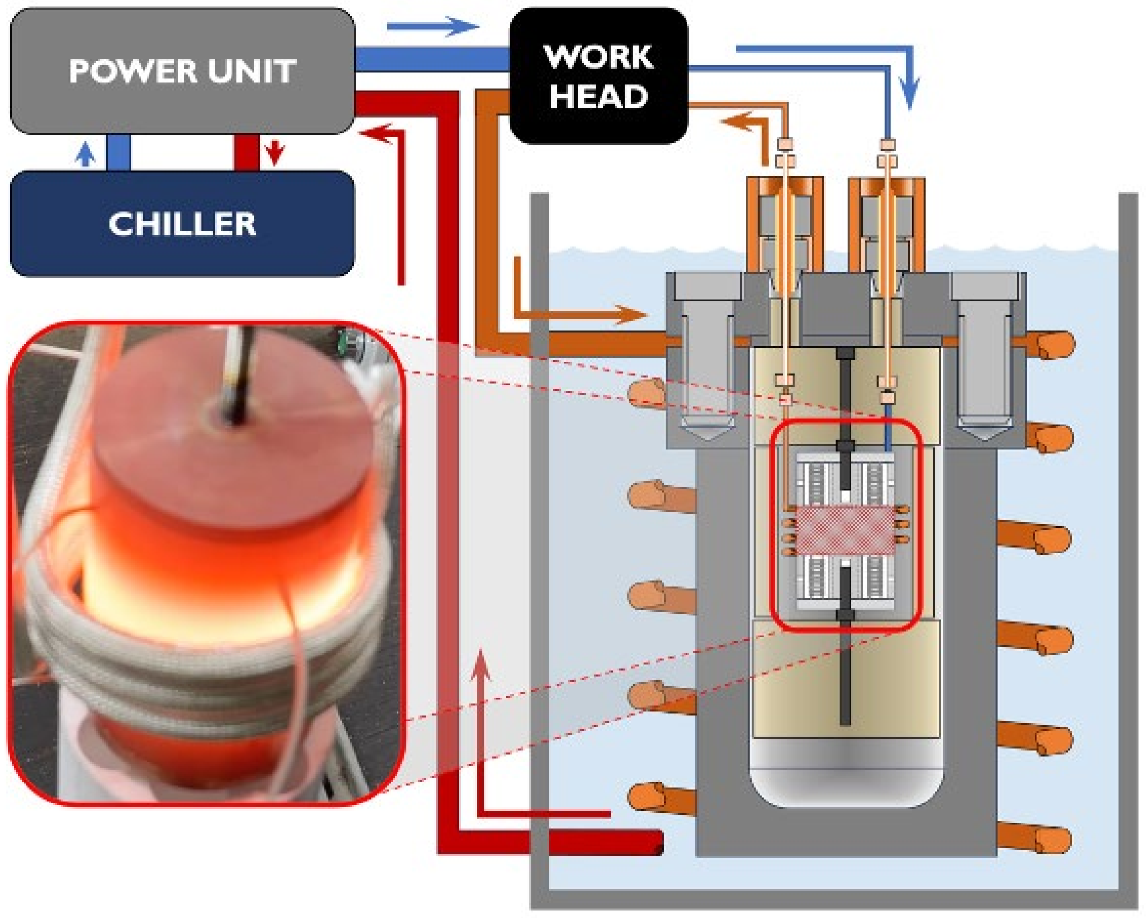


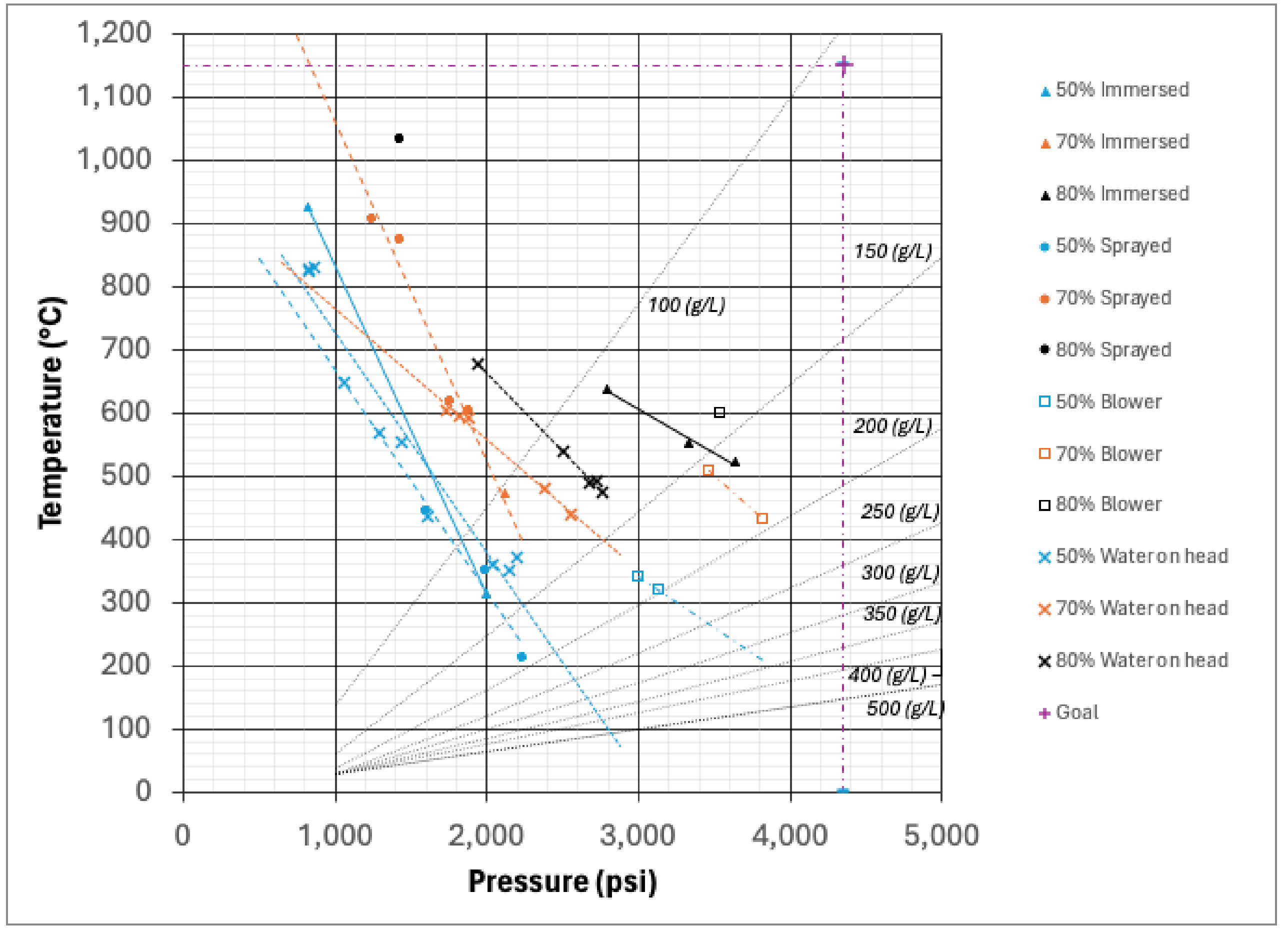
Autoclave Testing



- While commissioning and testing over multiple days have been completing, ongoing efforts underway for long duration testing (1,000 – 5,000 hrs.)

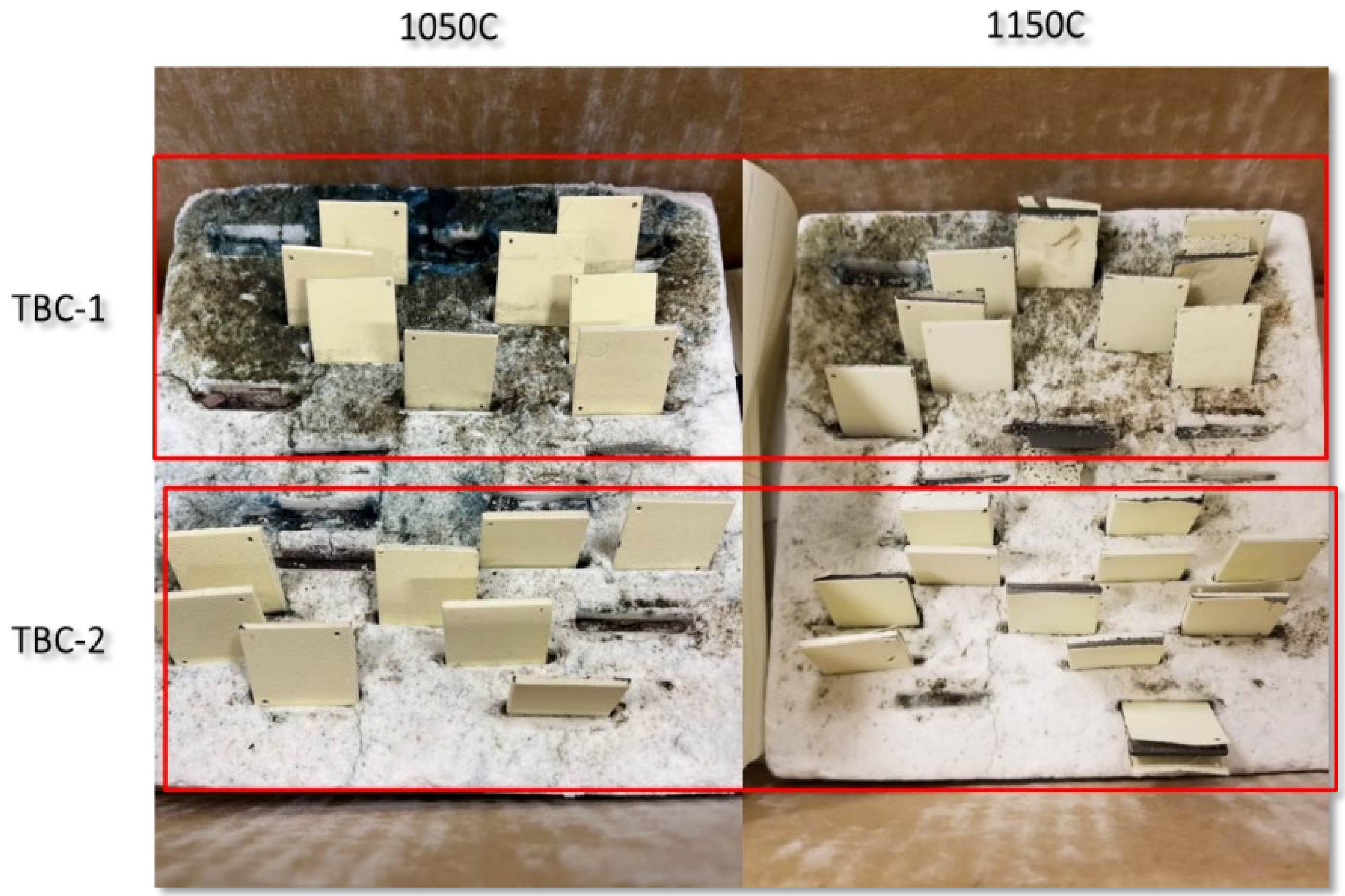
Autoclave Test Setup Modifications

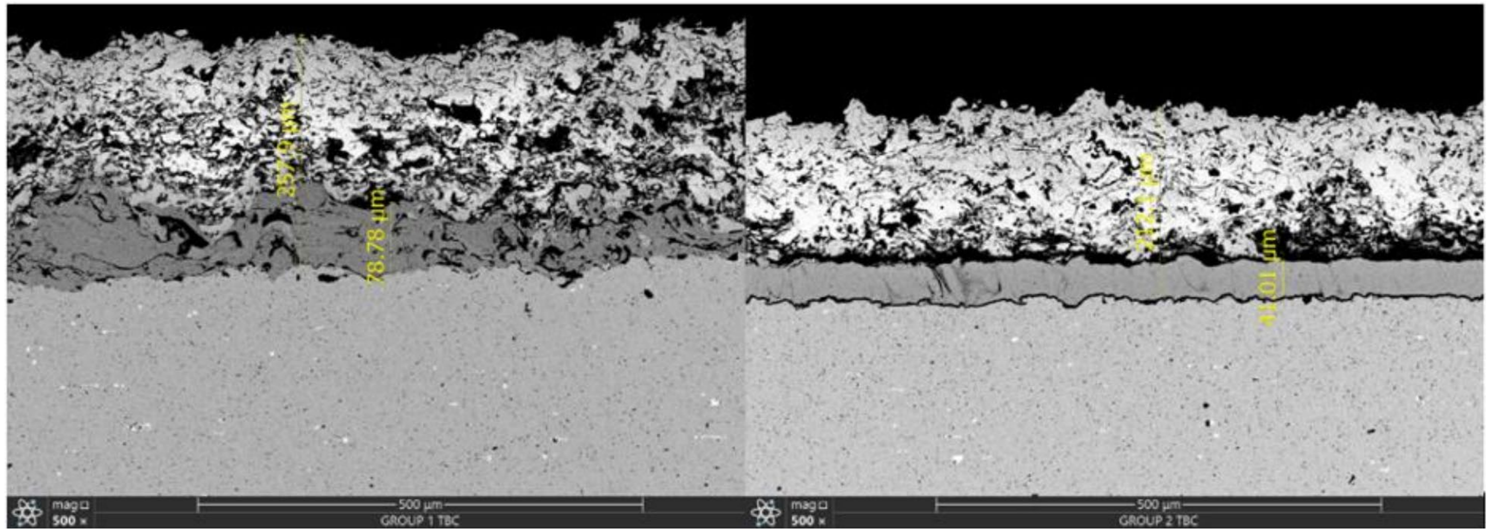




- Monolithic 310S specimen holder and susceptor.
- Improved reliability compared to graphite susceptor, decreased resistivity.

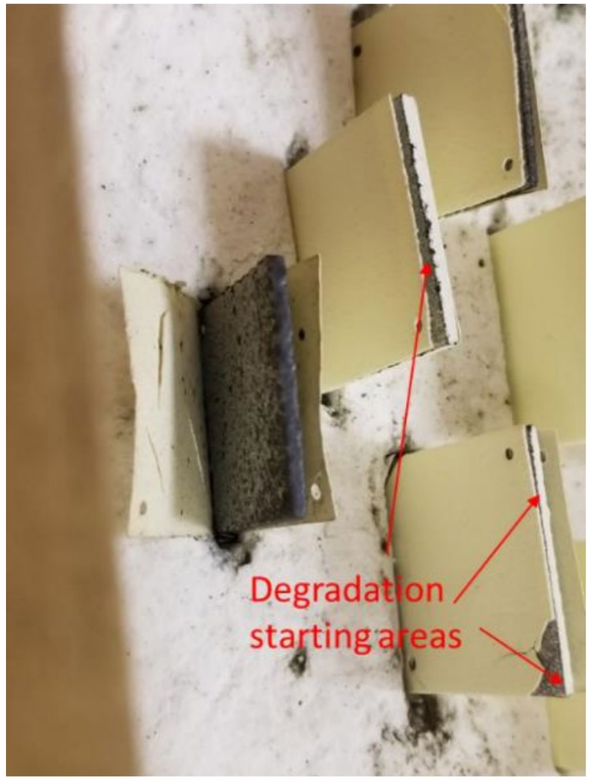
TBC Cyclic Testing

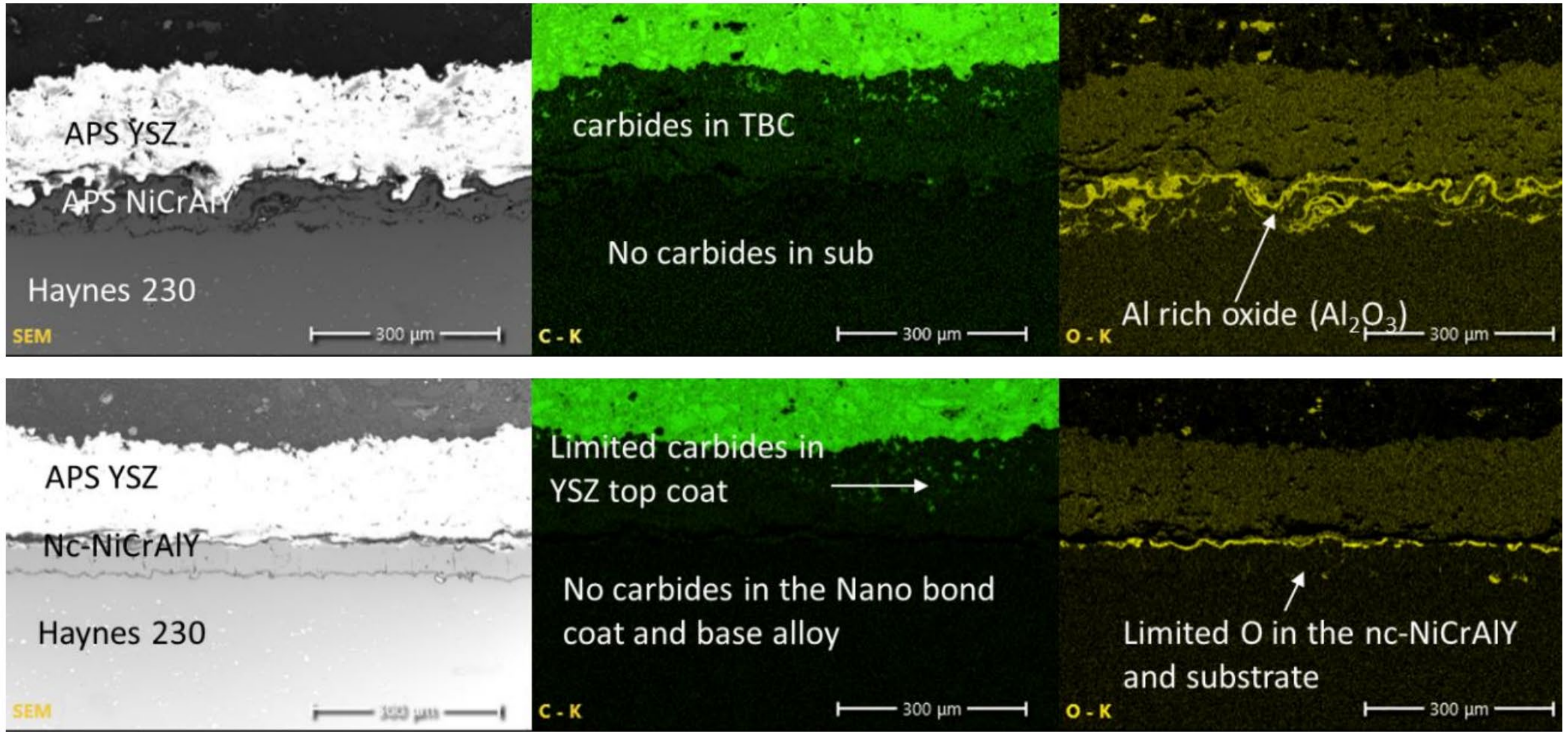




- 500 cycles
  - 50 min at (1050°C or 1150°C), ambient P
  - 10 min. forced air cooling.
- Two different coating methods on nickel alloy (Haynes 230 shown):
  - *Thermal spray* MCrAlY bond coat, *thermal spray* yttrium stabilized zirconia (YSZ) top coat.
  - *PEMS* MCrAlY bond coat, *thermal sprayed* (YSZ) top coat

TBC cyclic testing



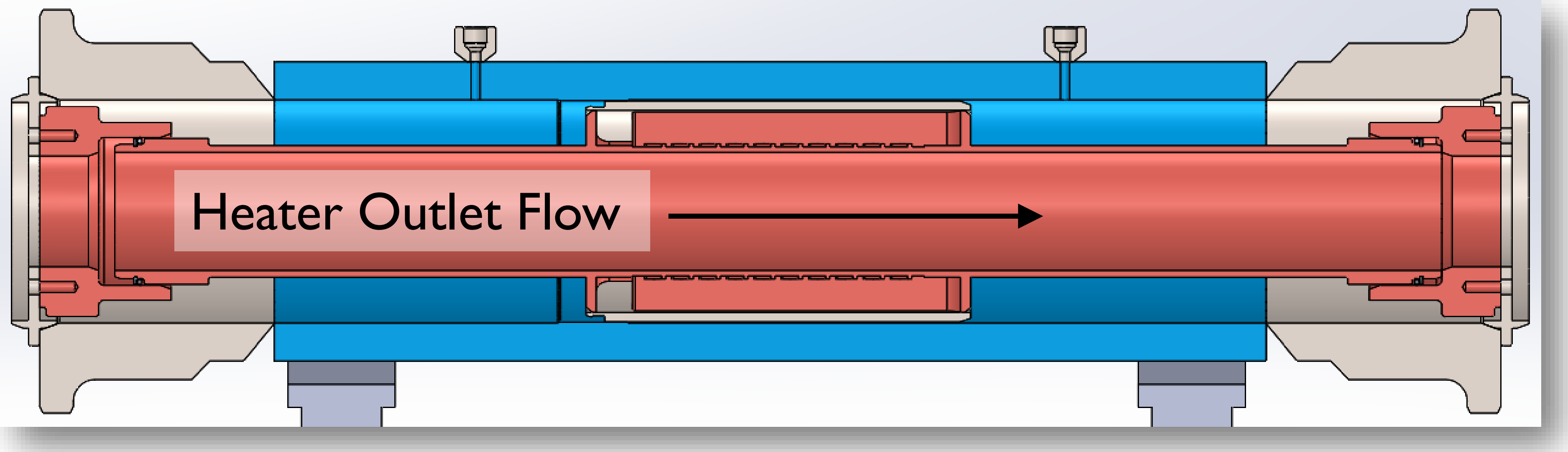


- Degradation seen on almost all samples for 1150°C cycling.
- PEMS bond coat witnessed significantly less carbon and oxygen attack than thermal sprayed bond coat.

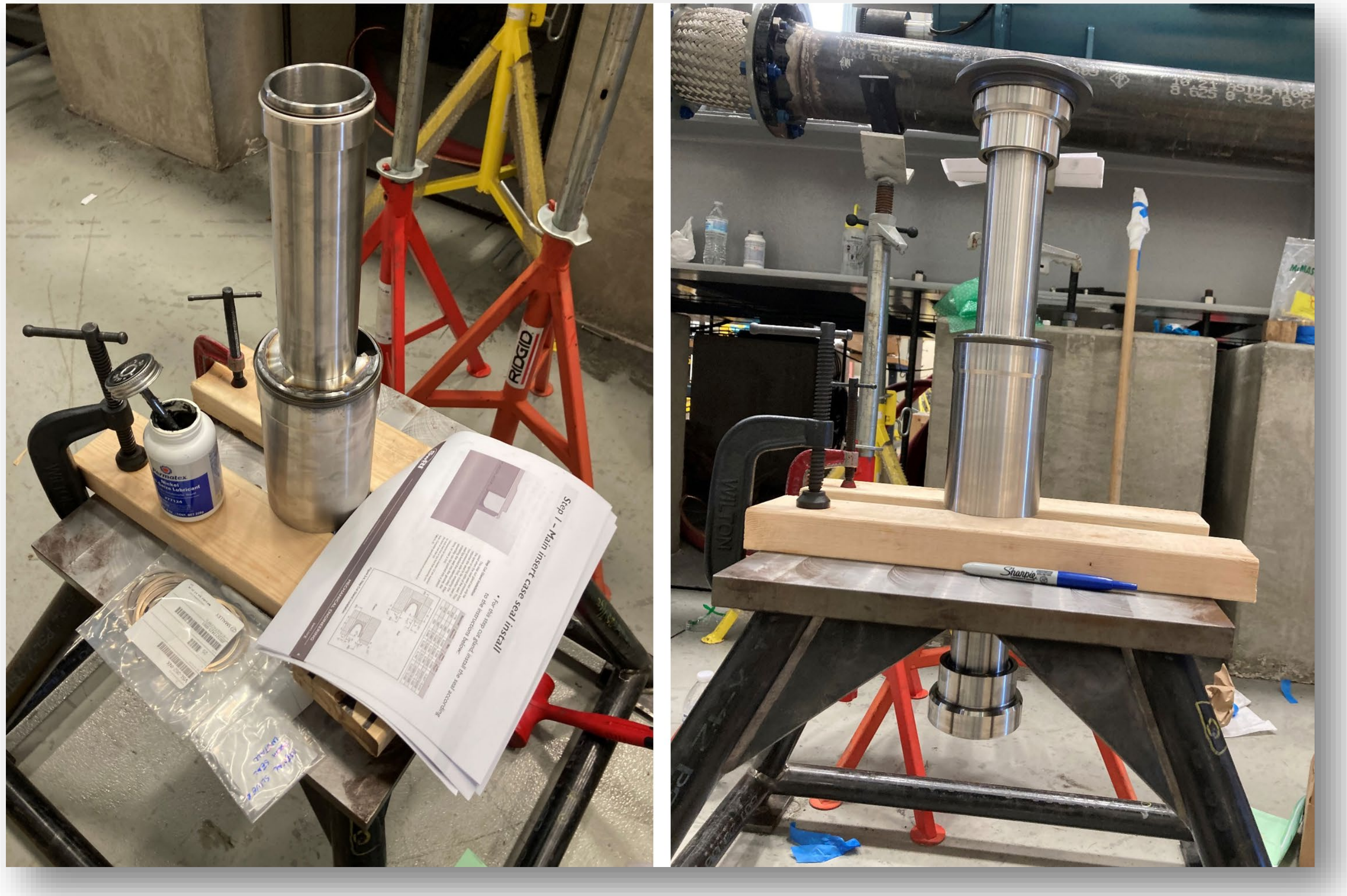
Component Testing

Midsection cooling

- A plethora of midsection ribbed cooling is available up to 50k RE number based on air-breathing engine.
- What happens with sCO_2 at internal cooling RE numbers 100k – 400k?

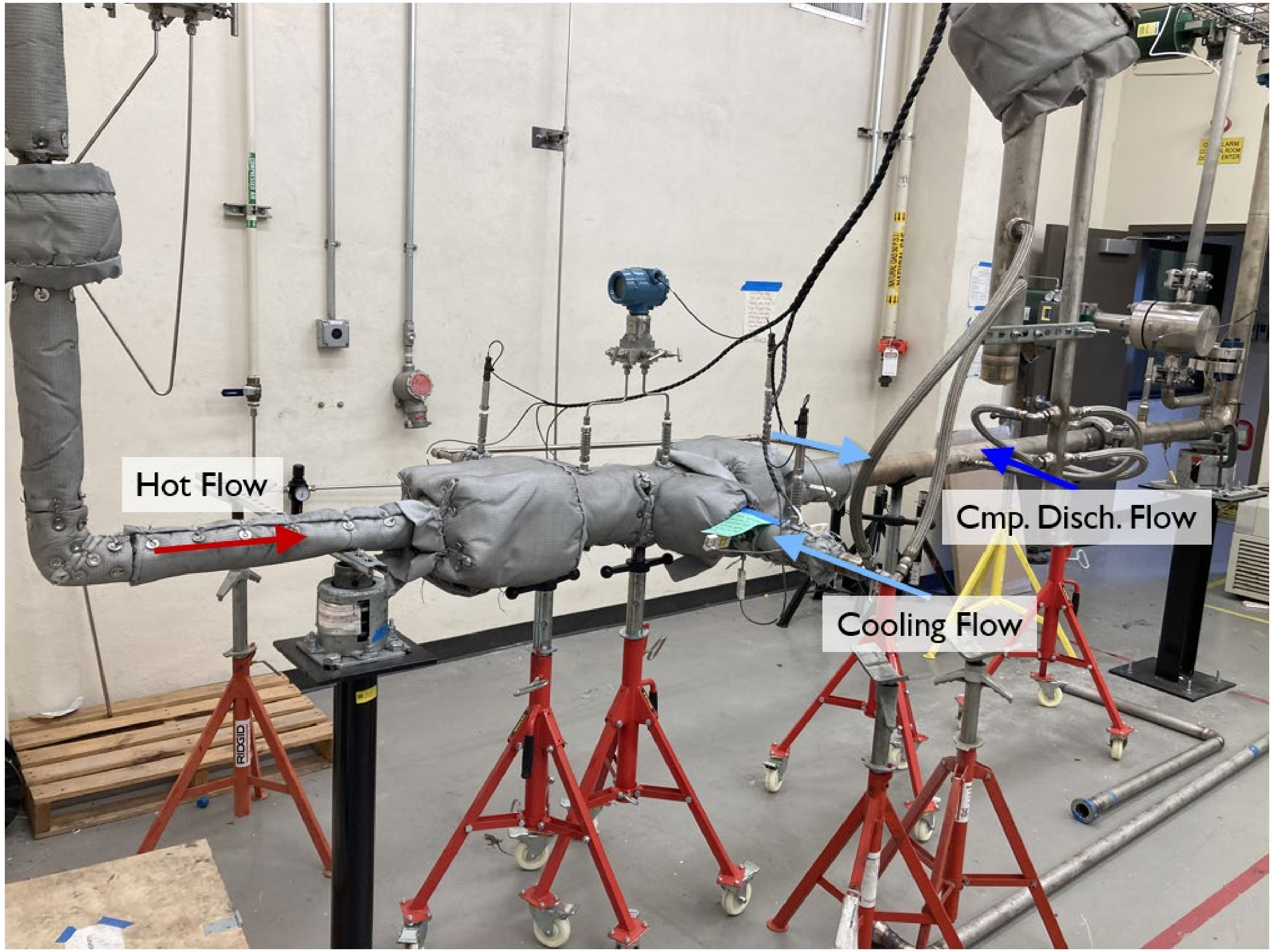


Test insert assembly



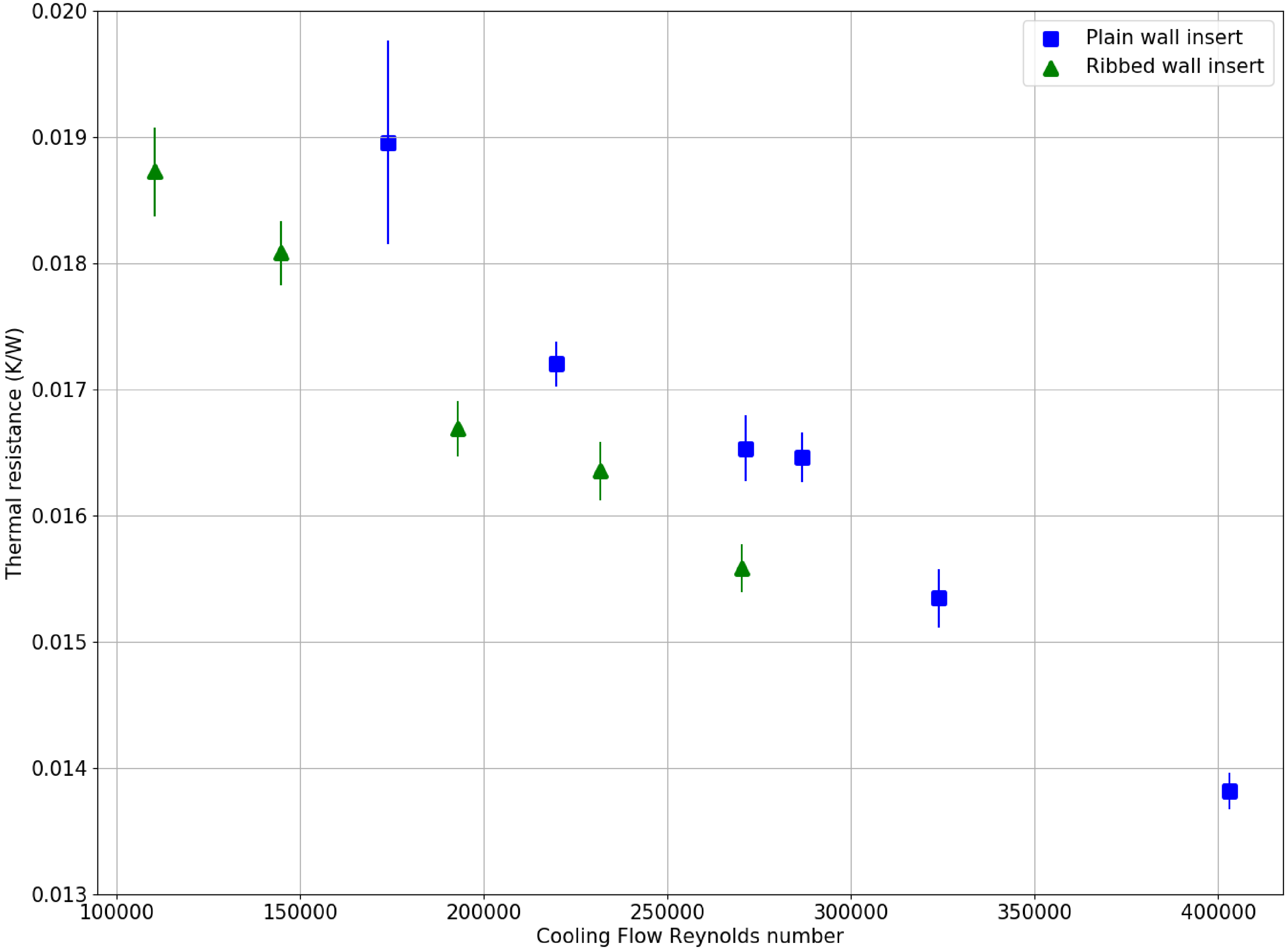
- Assembly and disassembly between interchangeable inserts can be completed in 5 hrs.

Test Setup and Conditions

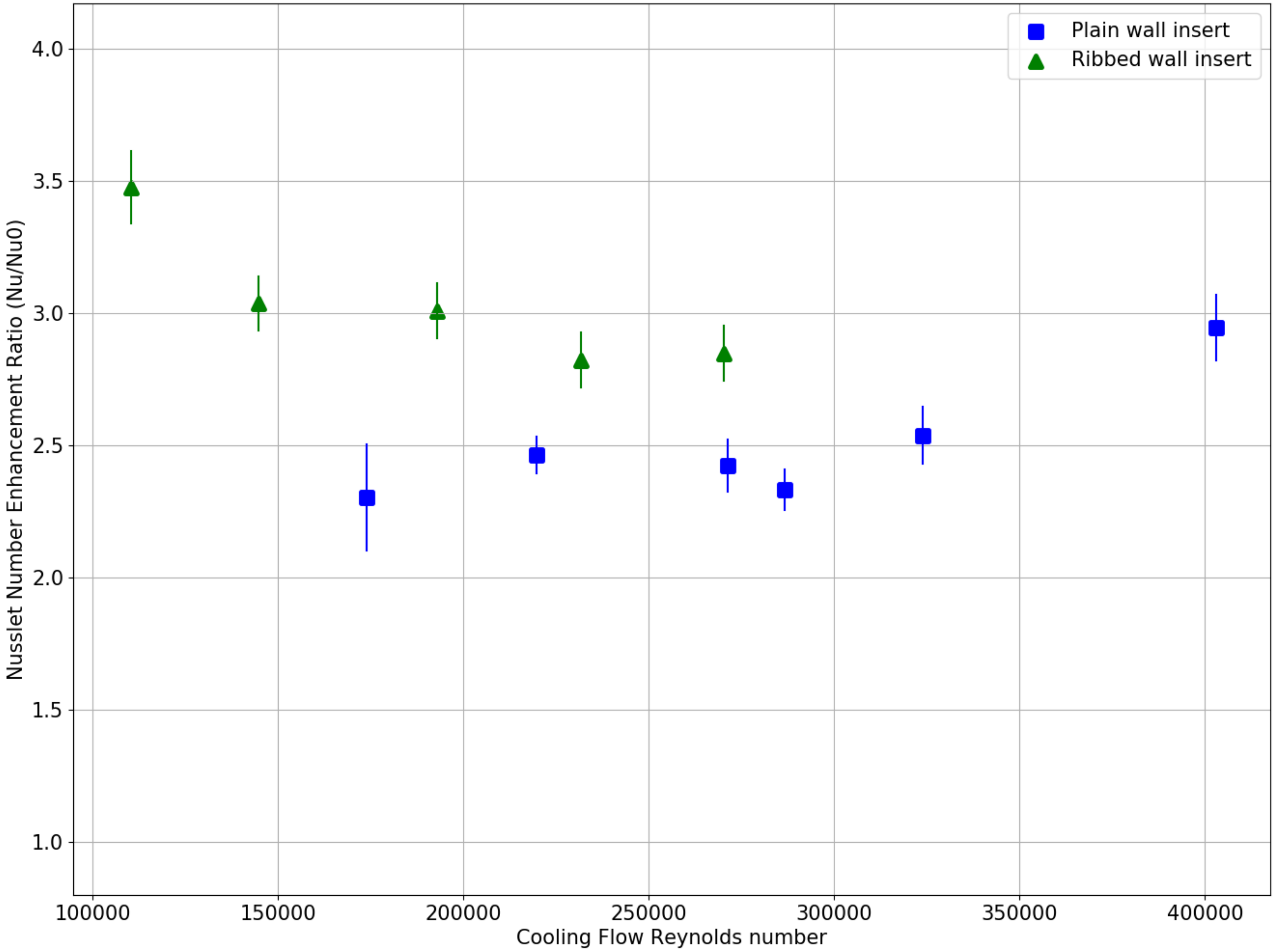


- Typical conditions:
  - Hot Flow: 200 bar, 410°C
  - Cooling Flow: 190 bar, 175°C

Comparing plain and ribbed wall tests – total thermal resistance



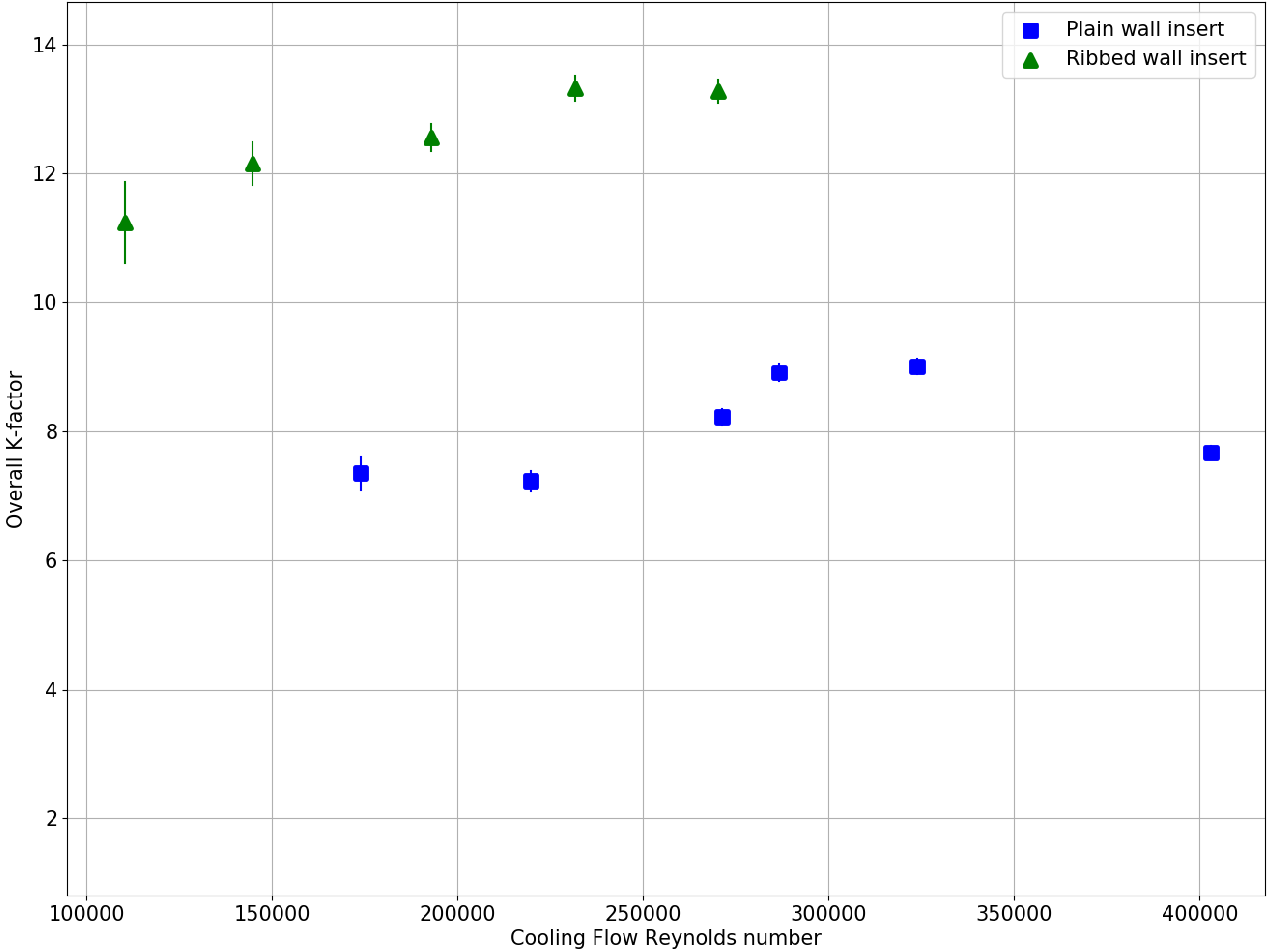
Comparing plain and ribbed wall tests – evaluated Nusselt number enhancement ratio



The parameter Nu/Nu0 compares the calculated test Nusselt number to a smooth wall Nusselt number calculated from the Gnielinski correlation for a fully developed internal passage with the same fluid conditions.

Pressure drop across serpentine passages

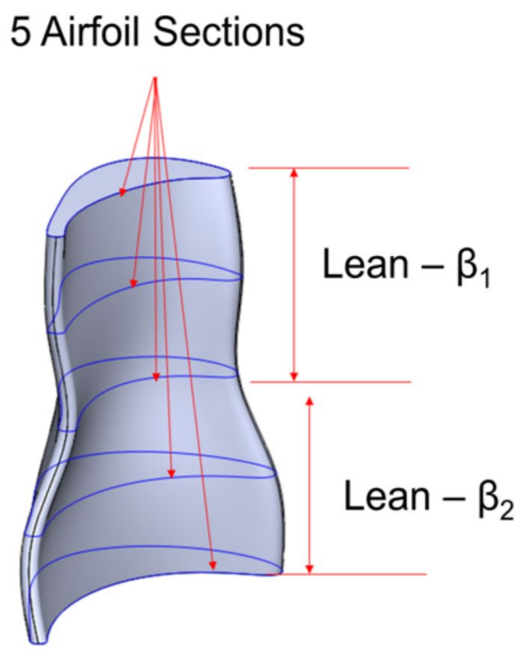
$$k = \frac{\Delta P}{\frac{\left(\frac{\dot{m}_{cool}}{2A_{pass}}\right)^2}{2\rho}}$$

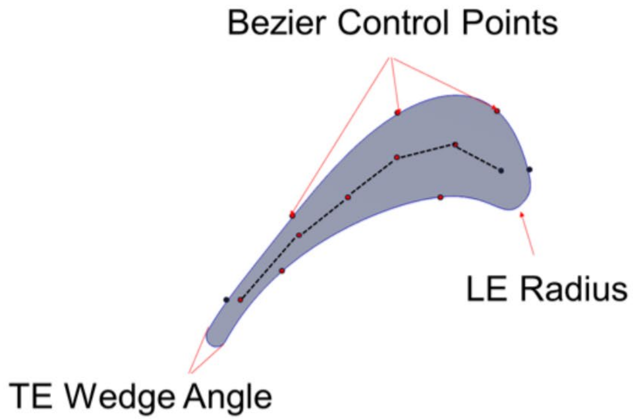


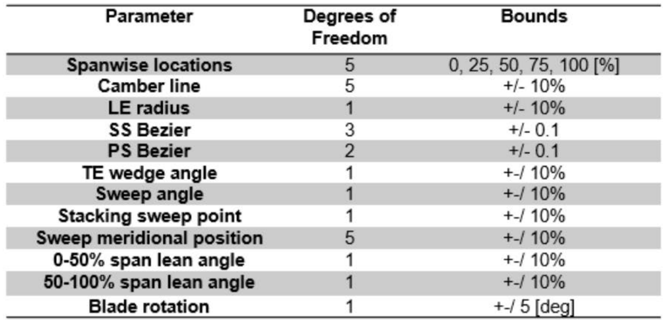
Takeaways from midsection internal cooling test

- Nusselt number enhancement ratios near 3 can be expected based on the test data generated at pertinent Reynolds numbers for sCO_2.
- Friction factor ratios of up to 10 can be expected for a chevron ribbed passage with characteristics aligned with those used for testing.
- The case can be made that less penalty should be ascribed to the pressure losses for internal cooling geometry relative to a gas turbine.

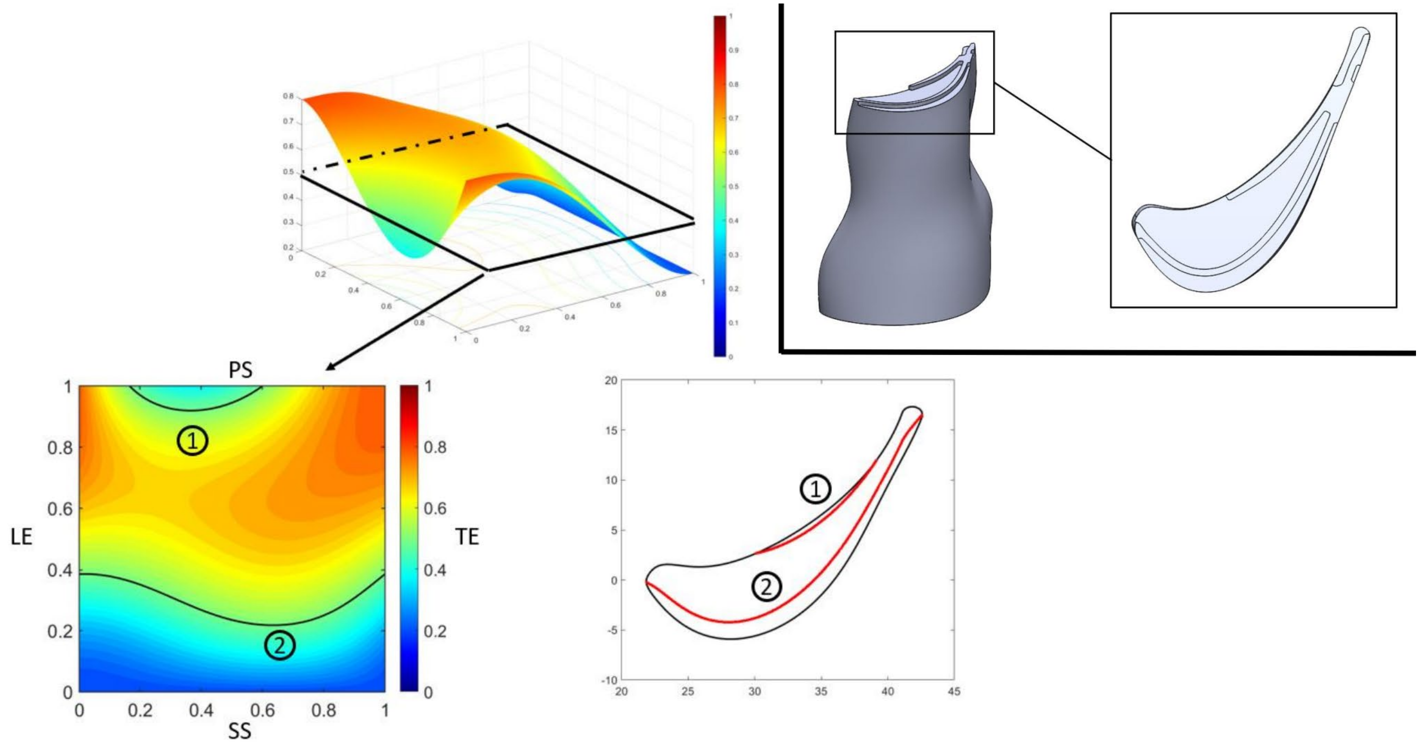
Background on 1st Stage Blade Optimization





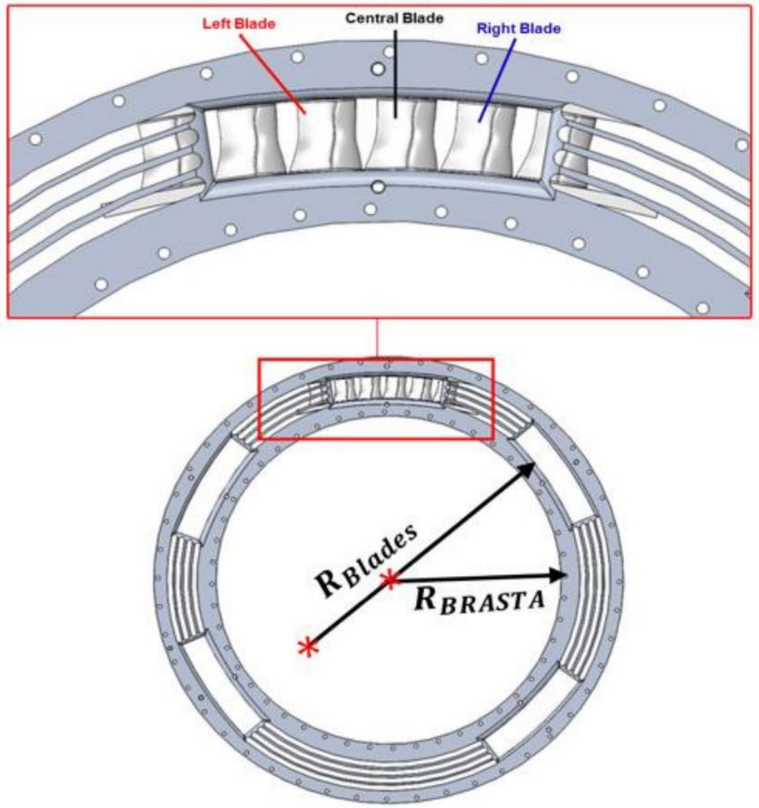


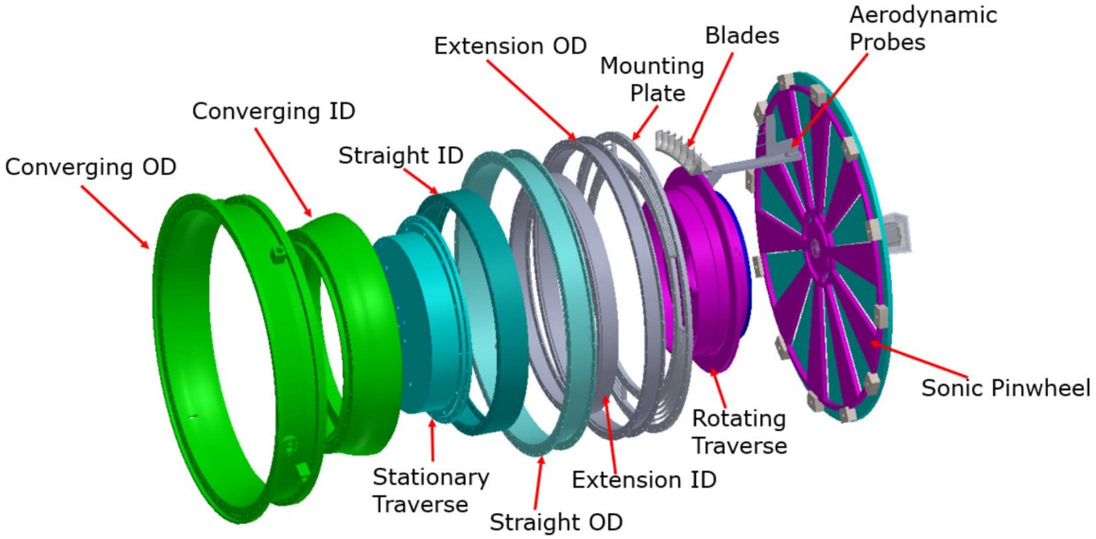
Parameter	Degrees of Freedom	Bounds
Spanwise locations	5	0, 25, 50, 75, 100 [%]
Camber line	5	+/- 10%
LE radius	1	+/- 10%
SS Bezier	3	+/- 0.1
PS Bezier	2	+/- 0.1
TE wedge angle	1	+-/ 10%
Sweep angle	1	+-/ 10%
Stacking sweep point	1	+-/ 10%
Sweep meridional position	5	+-/ 10%
0-50% span lean angle	1	+-/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

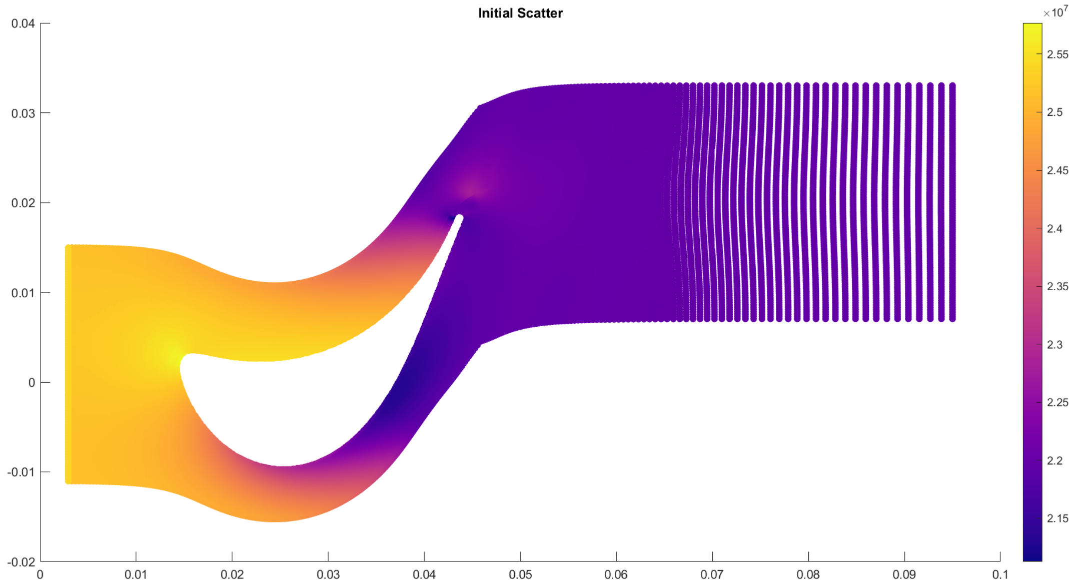
S1B cascade testing setup



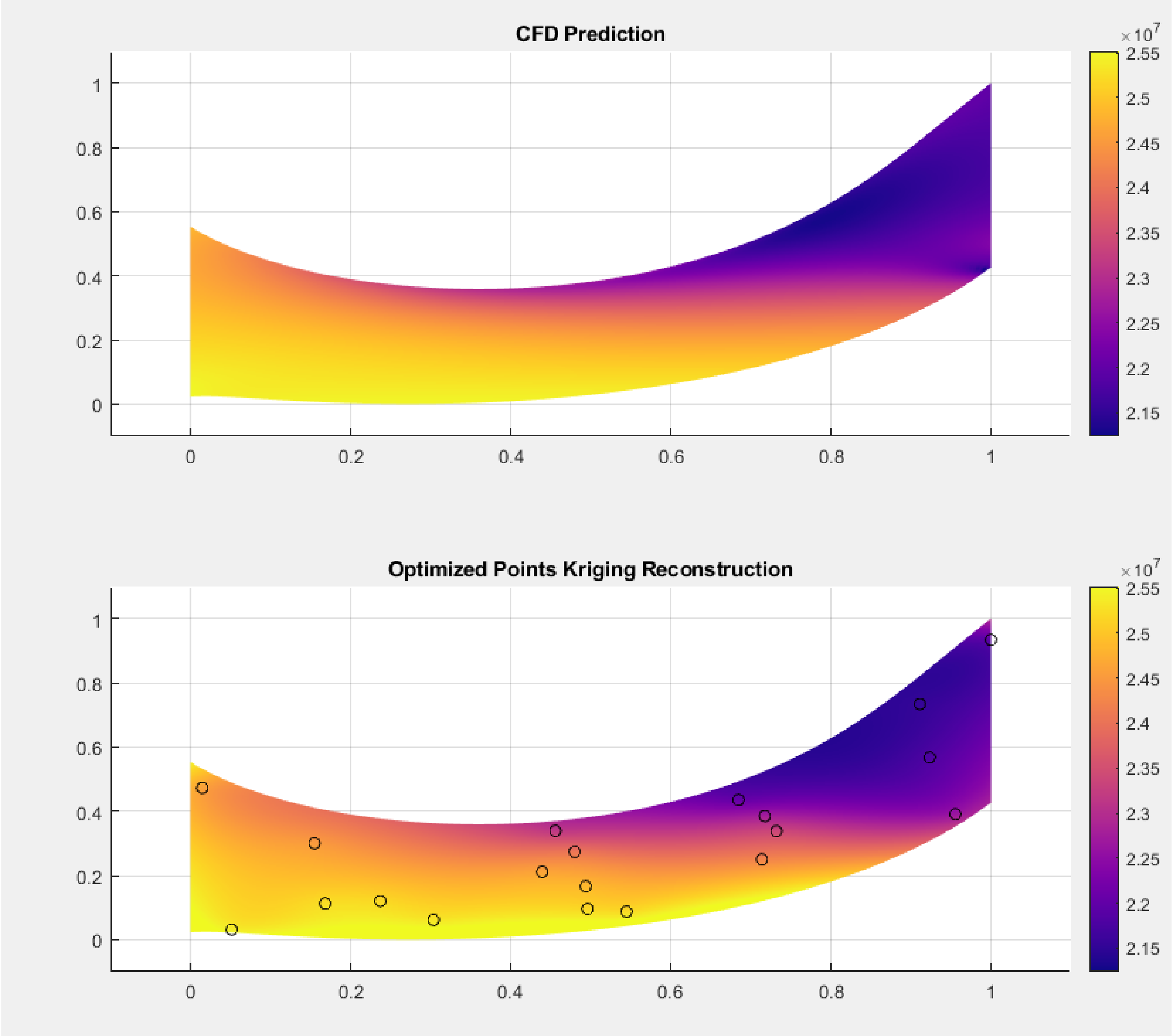


- The Purdue Big Rig for Aerothermal Stationary Turbine Analysis (BRASTA) is utilized with modifications for a S1B cascade test.

S1B cascade testing instrumentation

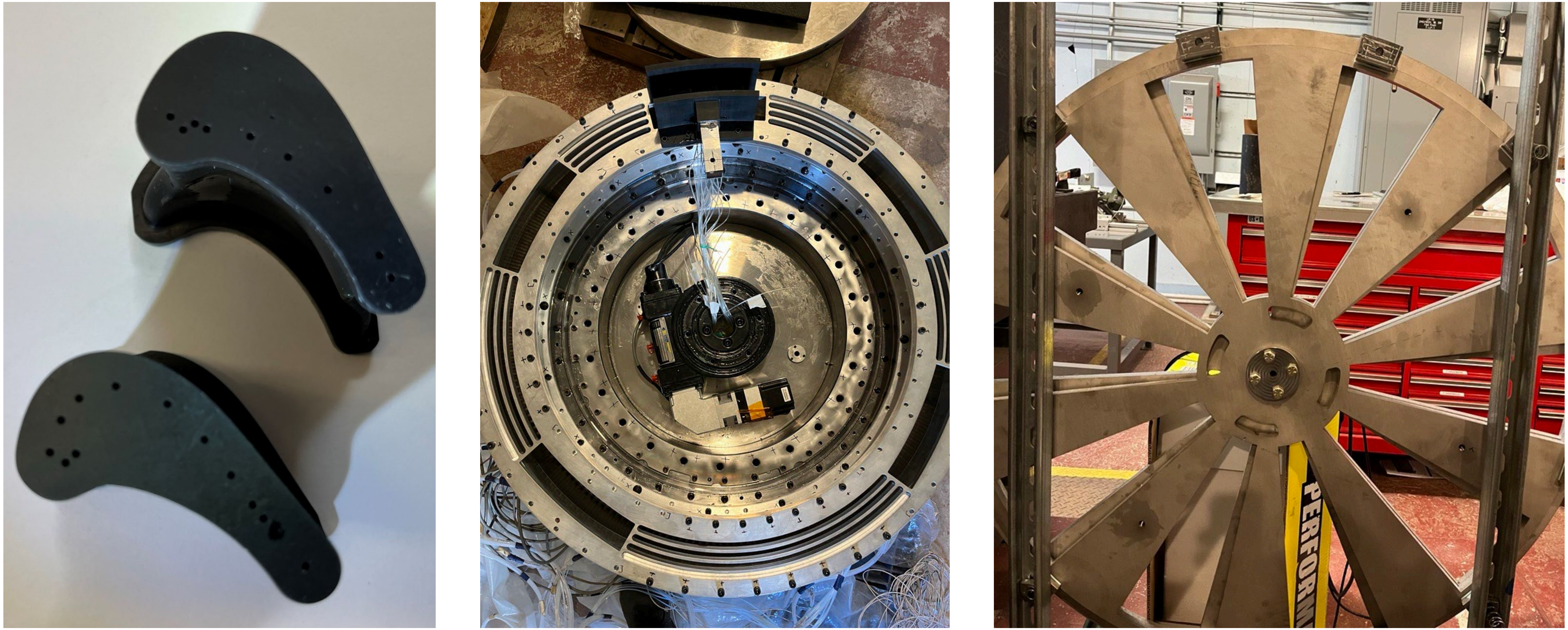

Initial Scatter

- Optimization methods are being used based on CFD analysis to optimize pressure tap location to reconstruct blade loading.


CFD Prediction

Optimized Points Kriging Reconstruction

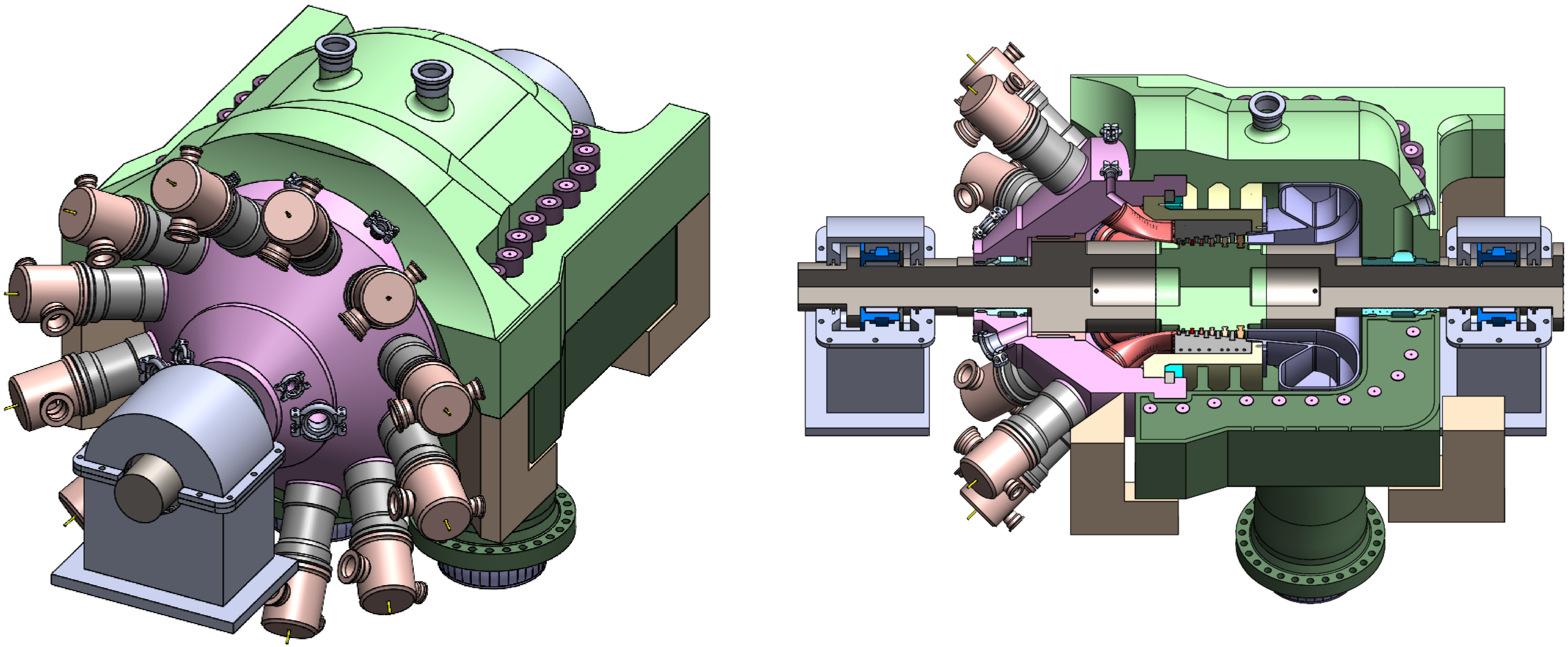
Test Rig Build



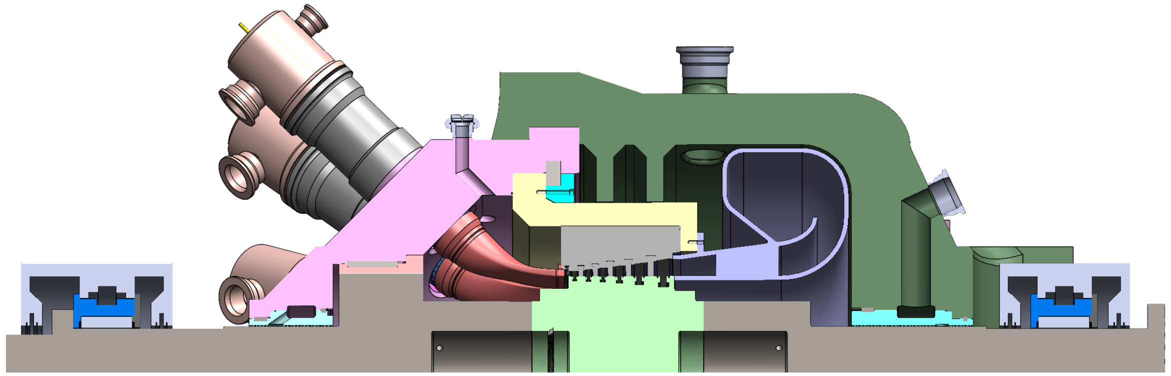
- Pressure tap locations installed in blade, with blade scans completed for comparison to nominal geometry.
- Sonic pinwheel has been tested for its actuation to sweep Reynolds numbers.

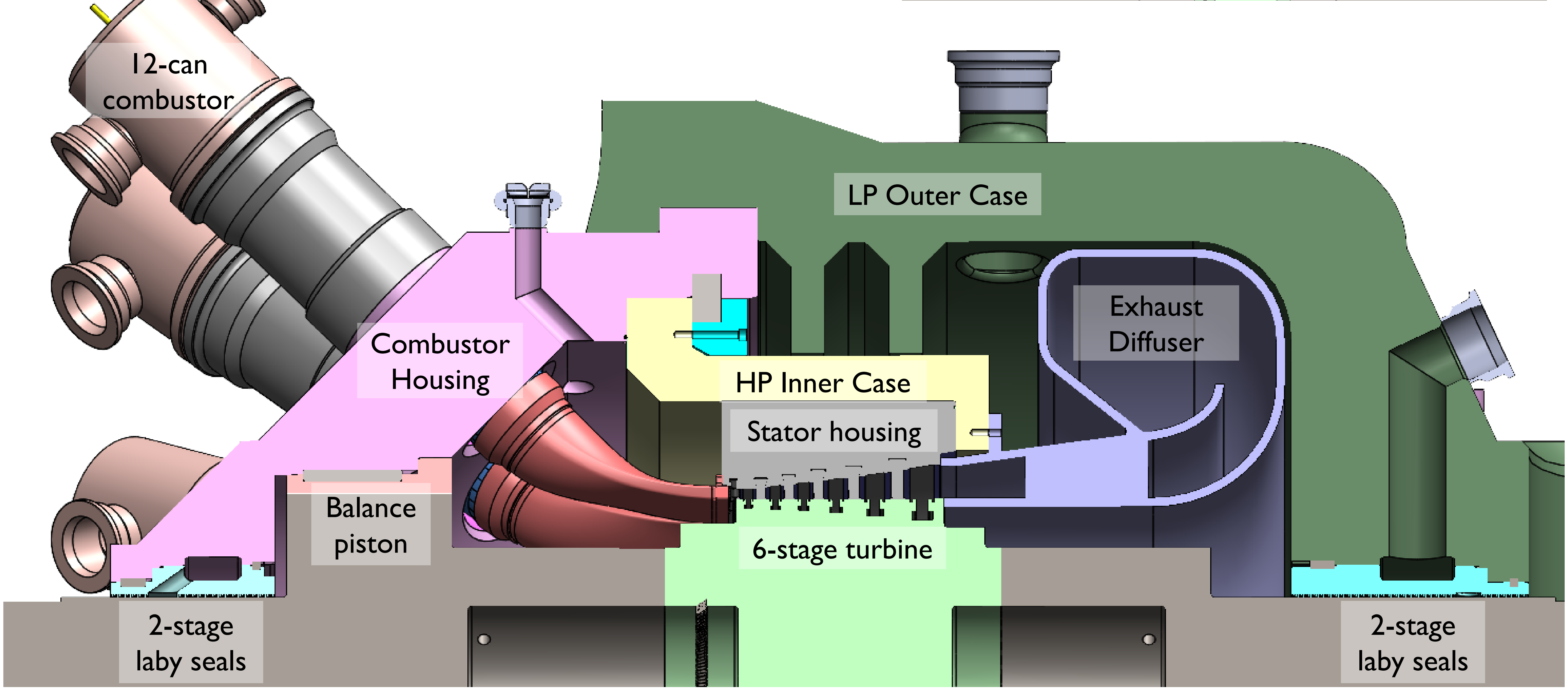
Turbine Design

Turbine Design

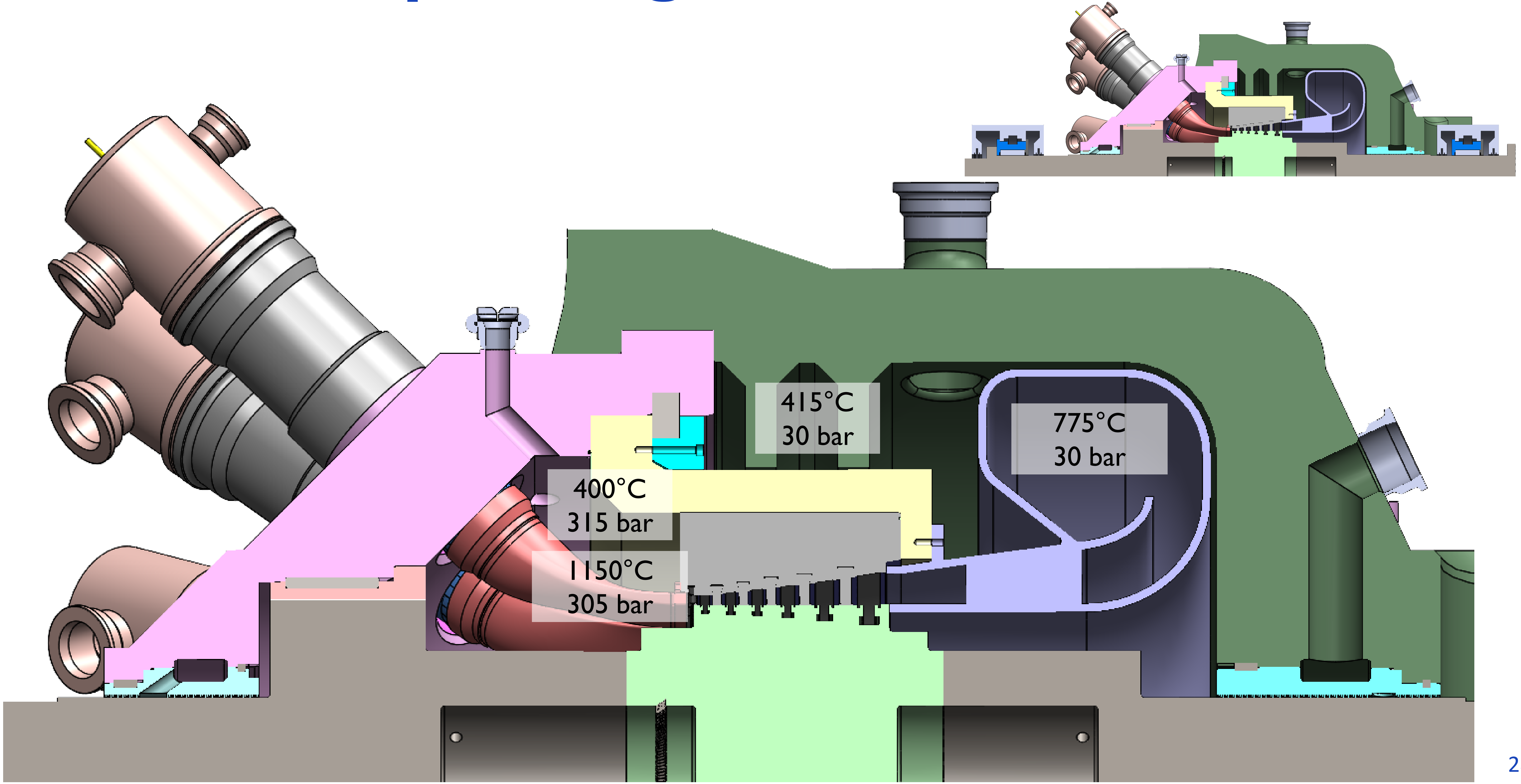


Turbine Design



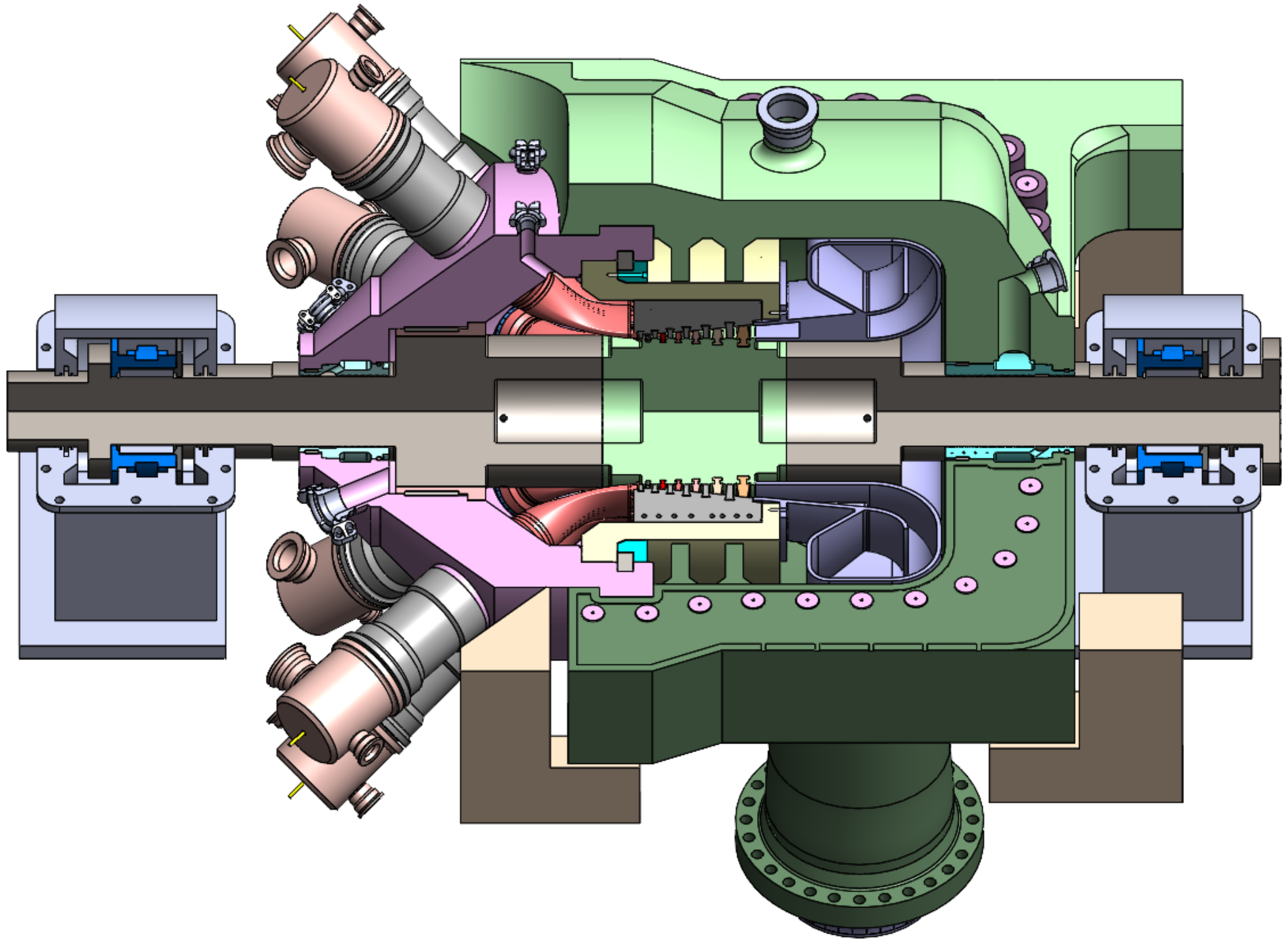


Standard Operating Conditions



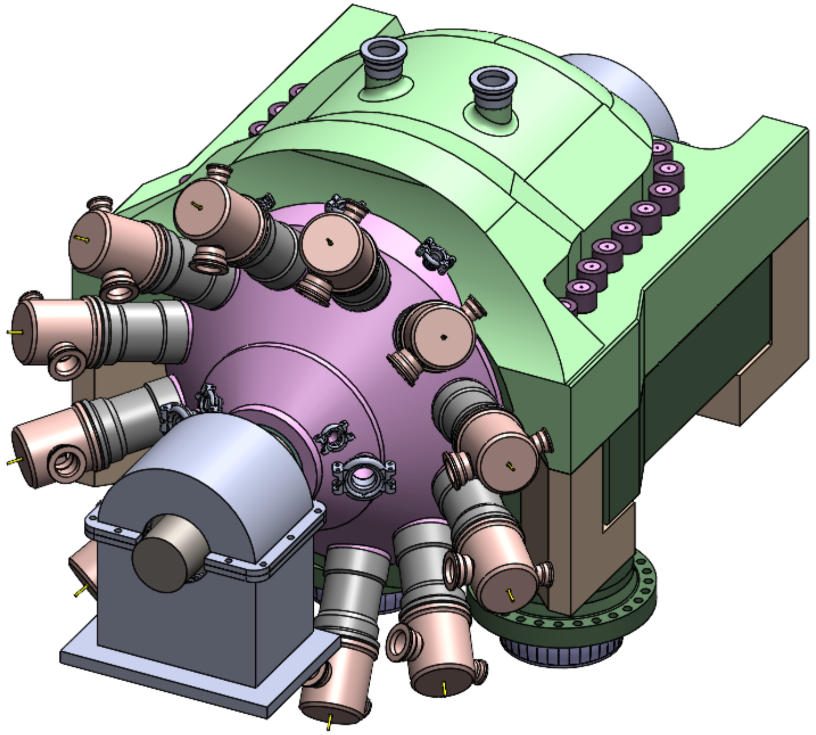
Target Design Criteria

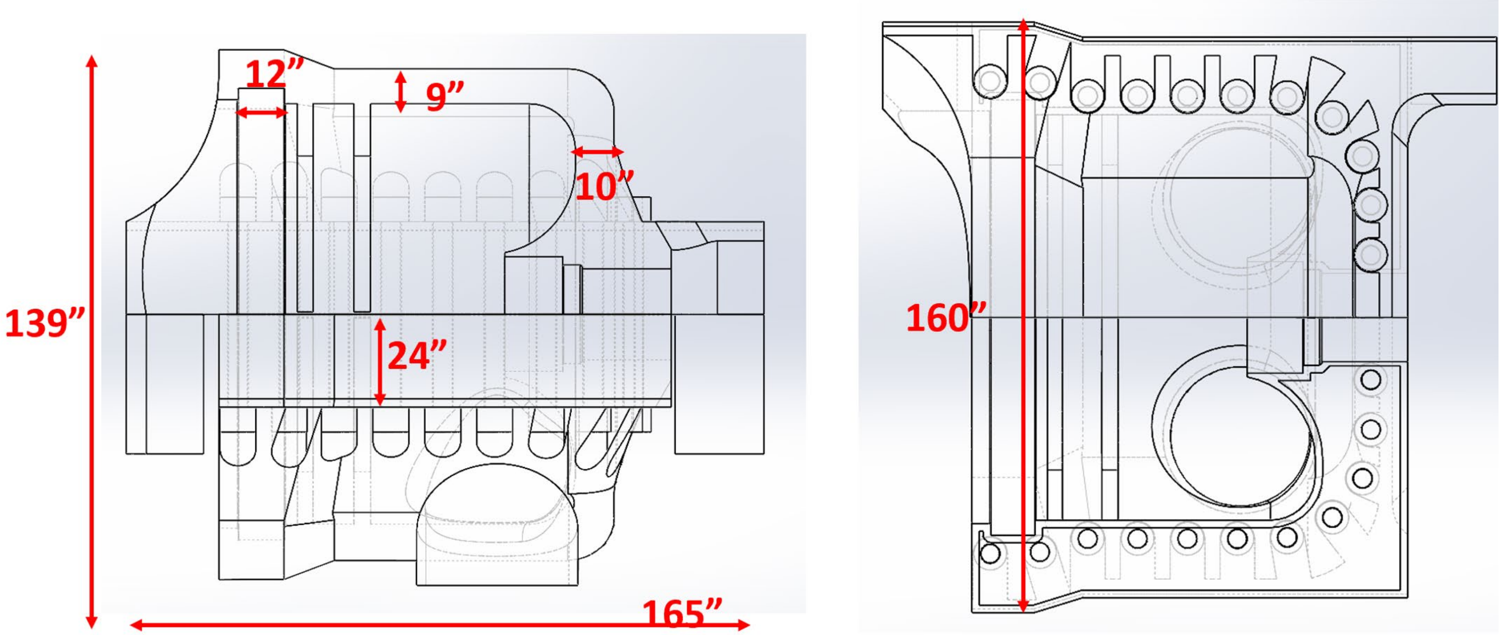
- Hot section component lifetime (combustor, transition duct, S1N, S1B): **30k hrs**
- Rotor lifetime: **150k hrs**
- Pressure containing components designed to ASME BPVC, Section VIII.
- Rotordynamics completed according to API standards.
- Mitigate capital cost through the following strategies:
  - 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



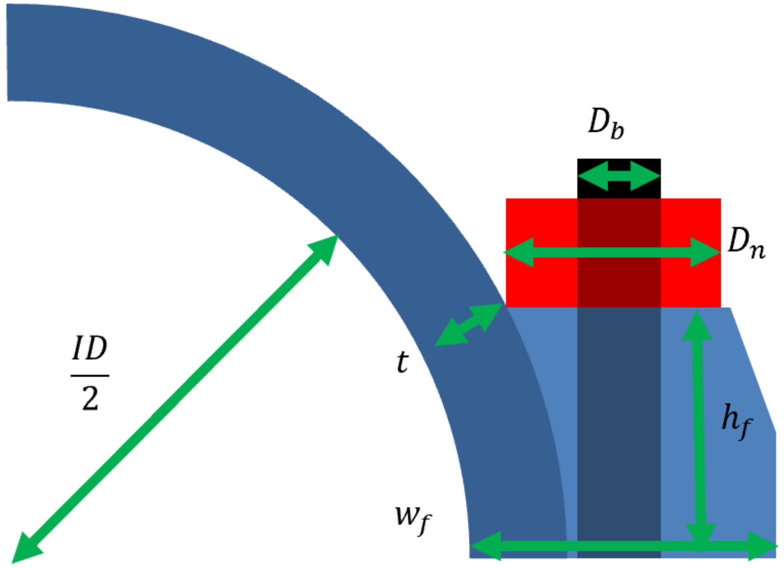


Design of the outer case leverages a group of design tools

Material	Sallow	Unit	Temp (°F)	Source
J22091	30.8E+3	psi	850	Input from BPVC Sec2.PtD.C.Table 5A
I740	40.0E+3	psi	800	Input from BPVC Code Case 2702-2
ss410	17.2E+3	psi	850	Input from BPVC Sec2.PtD.C.Table 3

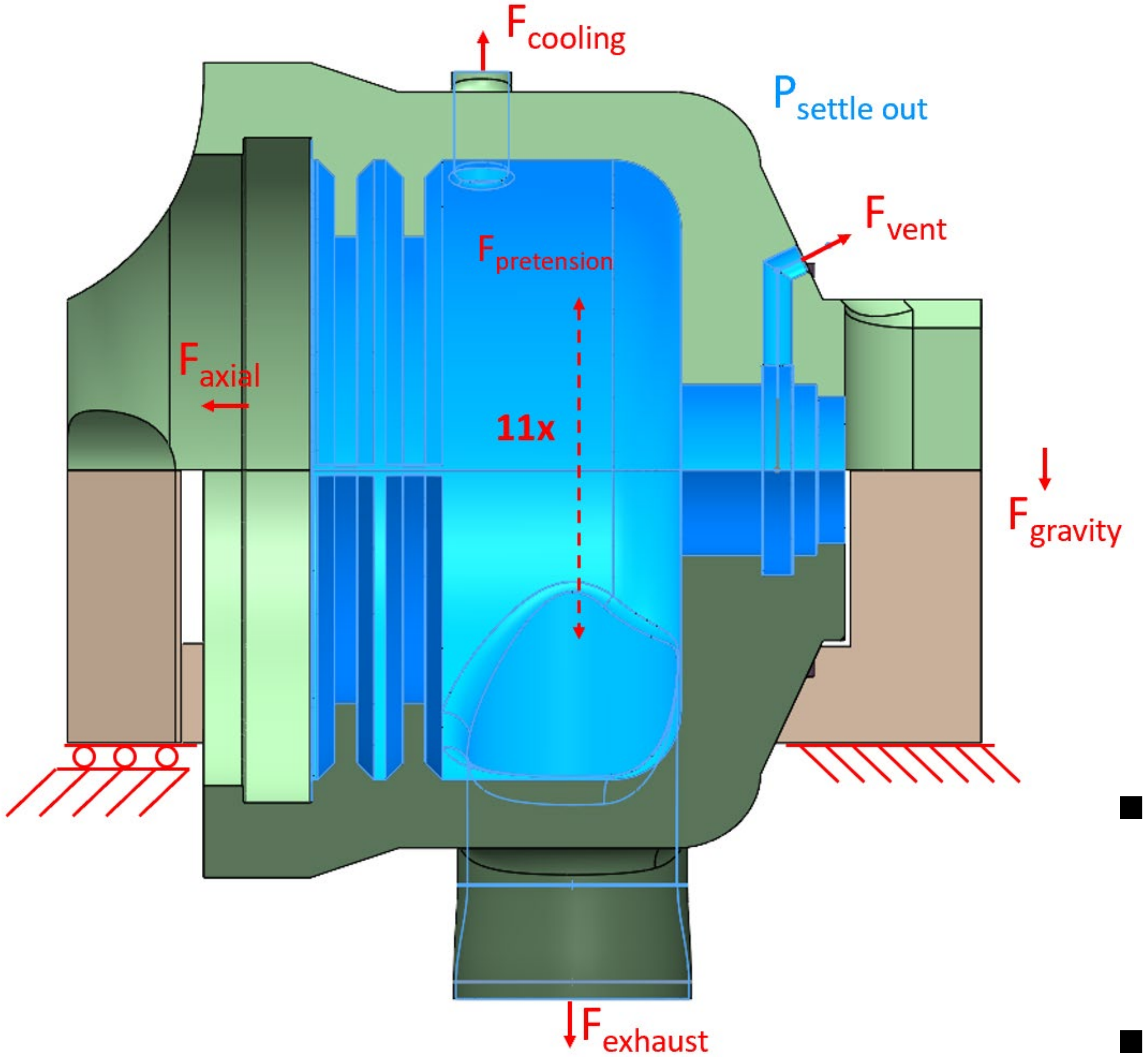
INNER CASE: Axial Load		23E+6	lbf
COMBUSTOR CASE: Axial Load		25.4E+6	lbf
OUTER CASE: Flange Separation Load		6.15E+6	lbf

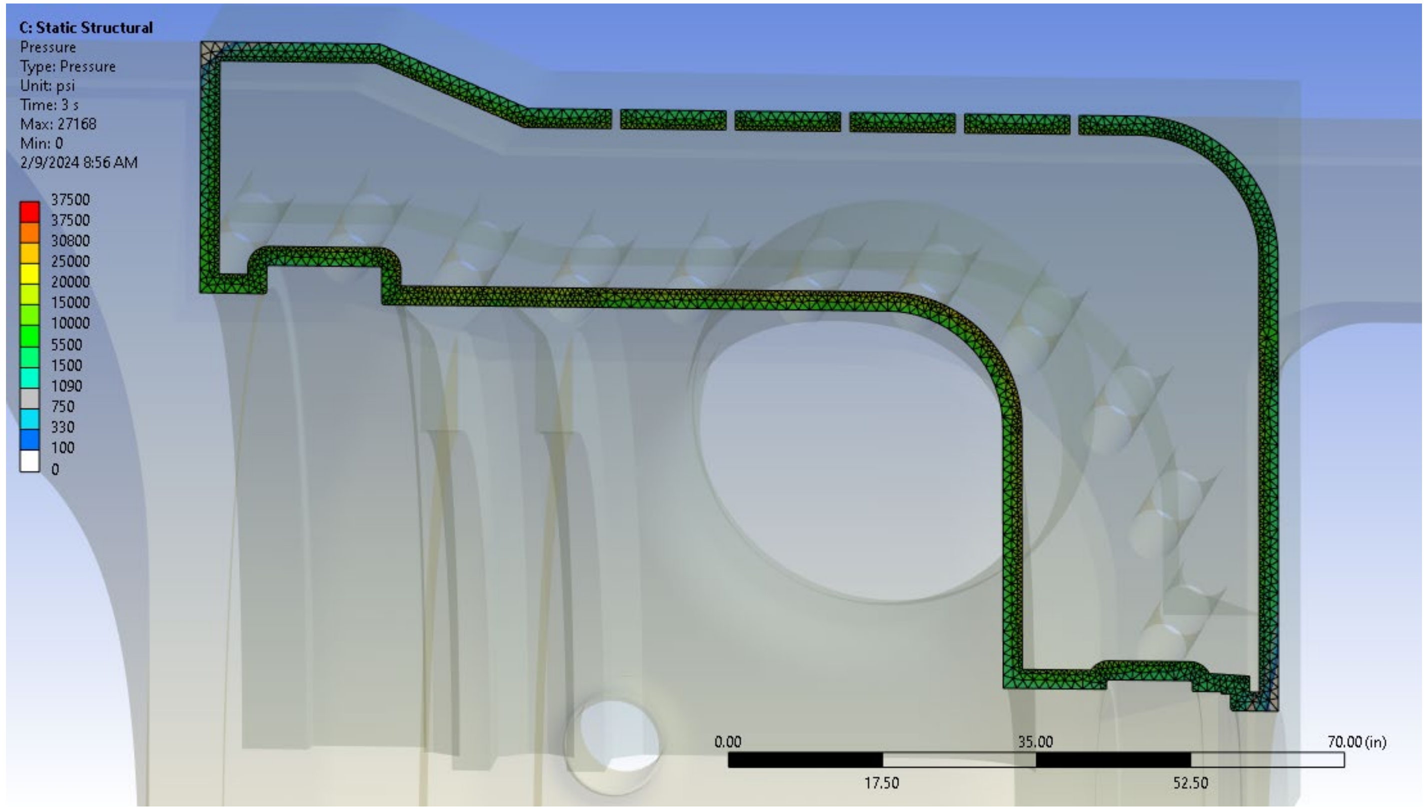
INNER CASE: Cylindrical Wall Thickness		5.03	in
COMBUSTOR CASE: Cylindrical Wall Thickness -		5.73	in
COMBUSTOR CASE: Cylindrical Wall Thickness -		7.60	in
OUTER CASE: Cylindrical Wall Thickness		1.27	in
OUTER CASE: Flange Width, Height	**Flange Width**	11.8	in
	Flange Height	10.05	in
COMBUSTOR CASE - INNER CASE: Rail Fit	**Shear Ring Width**	4.33	in
	Depth of Engagement	2.50	in
	Edge Margin	7.92	in
COMBUSTOR CASE - OUTER CASE: Rail Fit	**Shear Ring Width**	1.11	
	Depth of Engagement	0.640	
	Edge Margin	1.943	



Matl	**S_bolt_allow (psi)**	**Total Bolt Count**																					**Nut Diam**
K14072.a	25100	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**	**32**	**34**	**36**	**38**	**40**	**42**	**in**
Bolt Diameter	**3**	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	ps	ps	ps	ps	5.433
	3.25	s	s	s	s	s	s	s	s	s	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	5.857
	3.5	s	s	s	s	s	s	s	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	6.281
	3.75	s	s	s	s	s	s	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	6.705
	4	s	s	s	s	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	p	7.129
	4.25	s	s	s	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	p	p	7.553
	4.5	s	s	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	p	p	p	7.977
	4.75	s	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	p	p	p	p	8.401
	5	s	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	p	p	p	p	p	8.825
	5.25	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	p	p	p	p	p	p	9.249
	5.5	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	p	p	p	p	p	p	p	9.673
	5.75	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	ps	p	p	p	p	p	p	p	10.097
	6	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	ps	ps	p	p	p	p	p	p	p	p	10.521

FEA used to verify design

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Pressure
Type: Pressure
Unit: psi
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Min: 0
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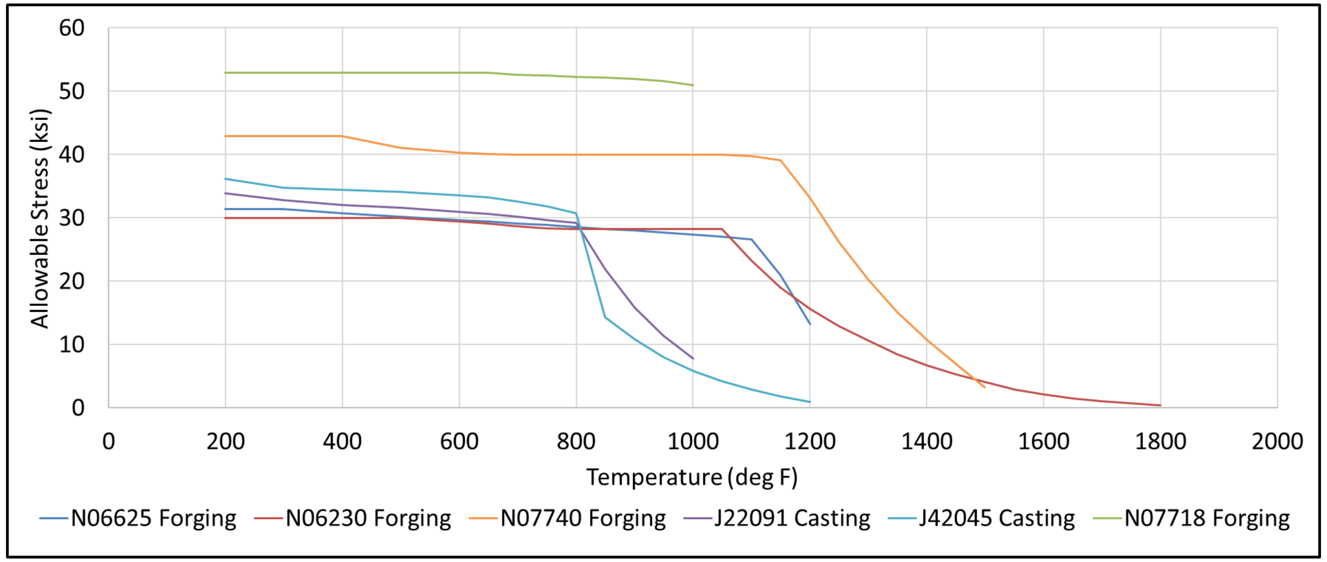
- FEA at nominal loads used to verify sealing pressure is maintained for split case.
- Limit load analysis converged according to BPVC Section VIII, Div. 2.

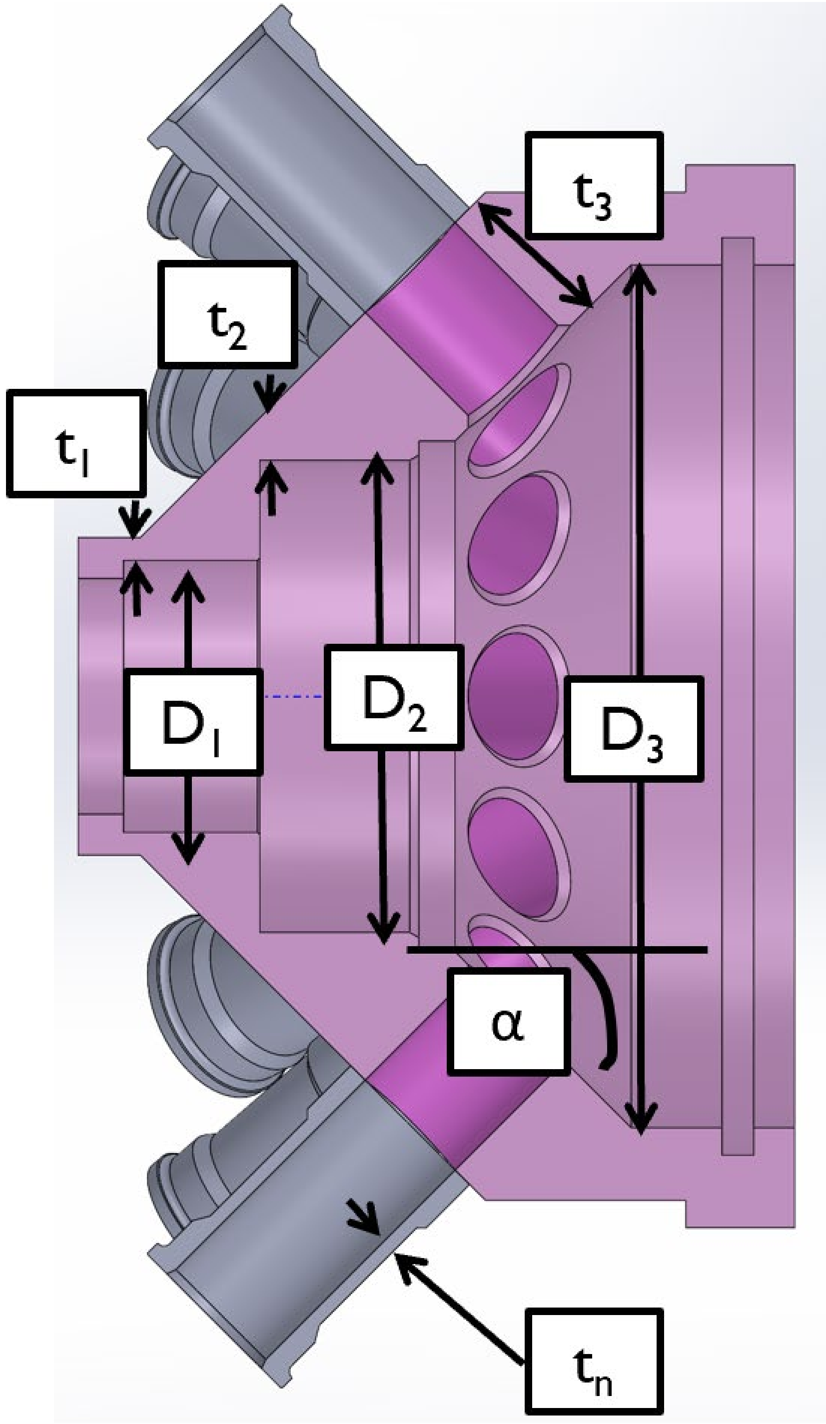
Design of the combustor housing

- ASME Section VIII, Div. 2, Part 4. used for initial thickness requirements:
  - Cylindrical Sections: $t = \frac{D}{2}\, exp\left(\left[\frac{P}{SE}\right] - 1\right)$
  - Conical Section: $t = \frac{D}{2\cos(\alpha)}\, exp\left(\left[\frac{P}{SE}\right] - 1\right)$



Minimum Required Thickness on Combustor Plenum*							
Rank	Material	t_1	t_2	t_3	t_n	1.5*t_3	1.5*t_n
5	N06230	2.60	4.50	11.63	0.89	17.45	1.34
4	N06625	2.56	4.43	11.45	0.98	17.18	1.47
3	J22091	2.50	4.33	11.20	-	16.80	-
2	J42045	2.36	4.09	10.56	-	15.84	-
1	N07718	1.34	2.32	5.99	0.51	8.99	0.77

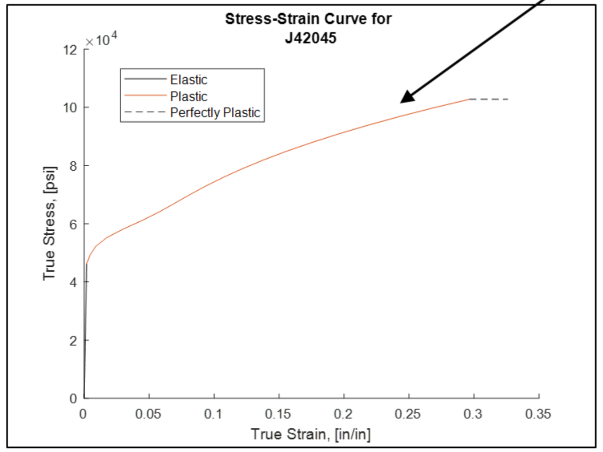
*conical section requires 1.5*thickness to accommodate 12 can holes

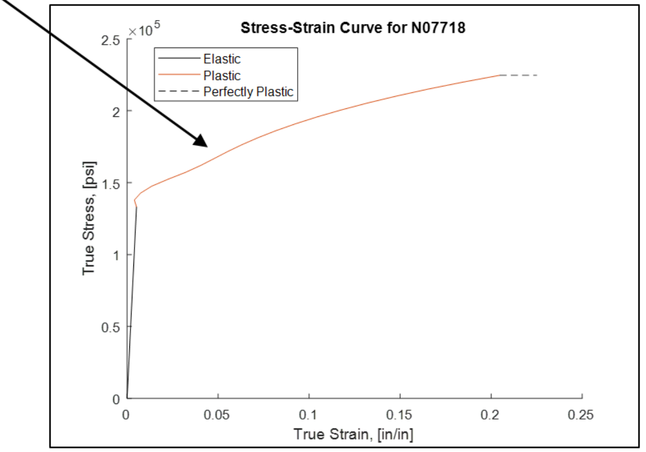


Design of the combustor housing

- Limit load and local failure analyses completed and converged according to Section VIII, Div. 2.
- Drawings currently being finalized for manufacturing process to obtain cost estimate, consisting of casting and welding before final machining.

Plastic strain region tabulated into FEA material model

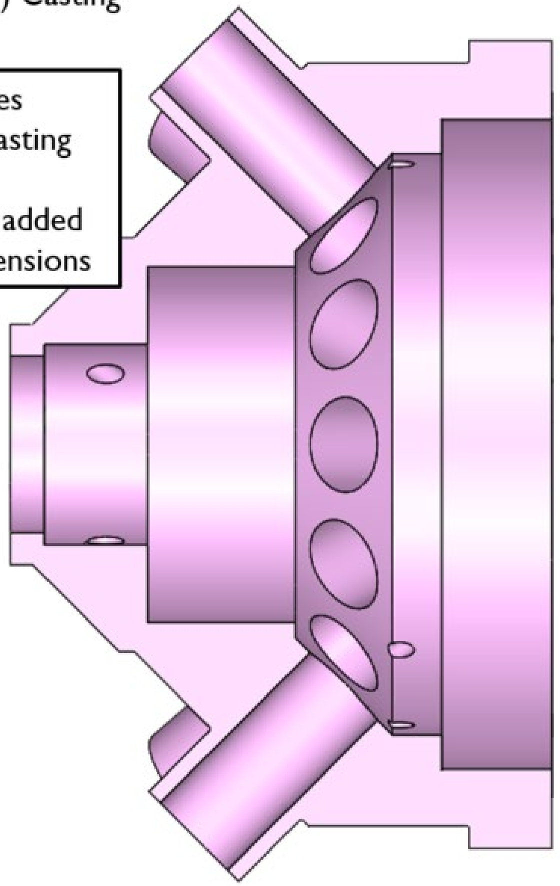




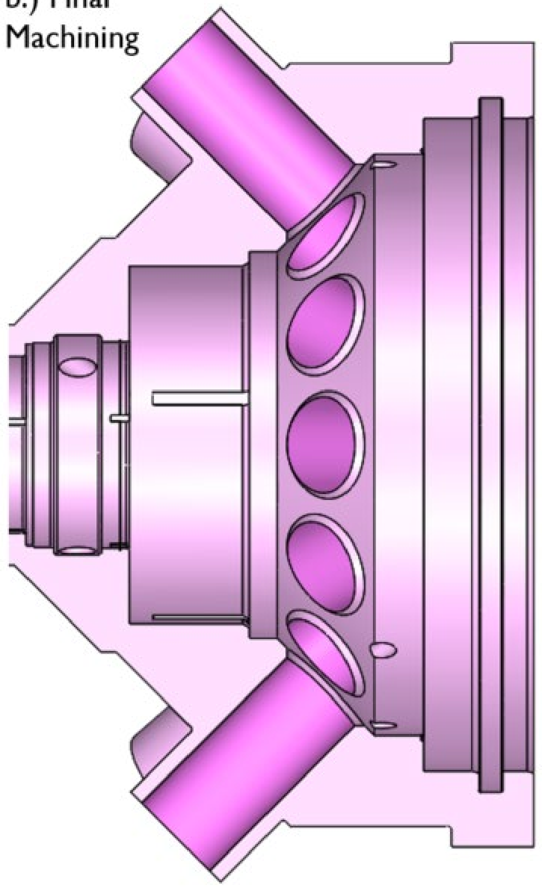
a.) Casting

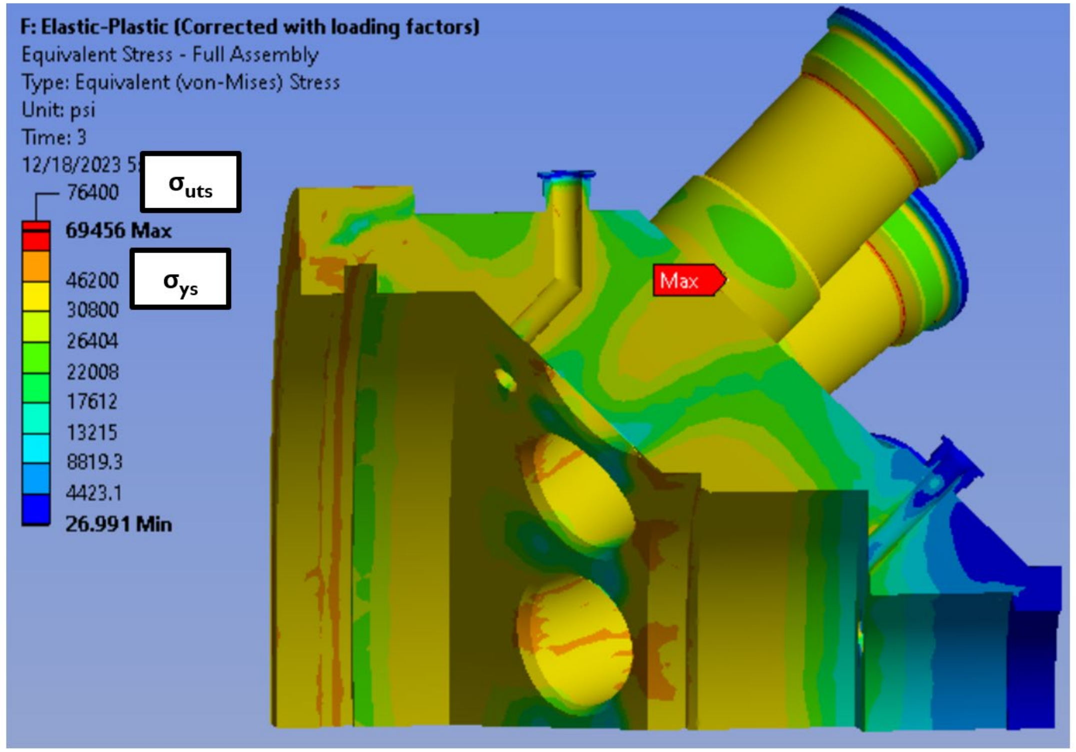
Internal features removed for casting

Extra material added to critical dimensions



b.) Final Machining

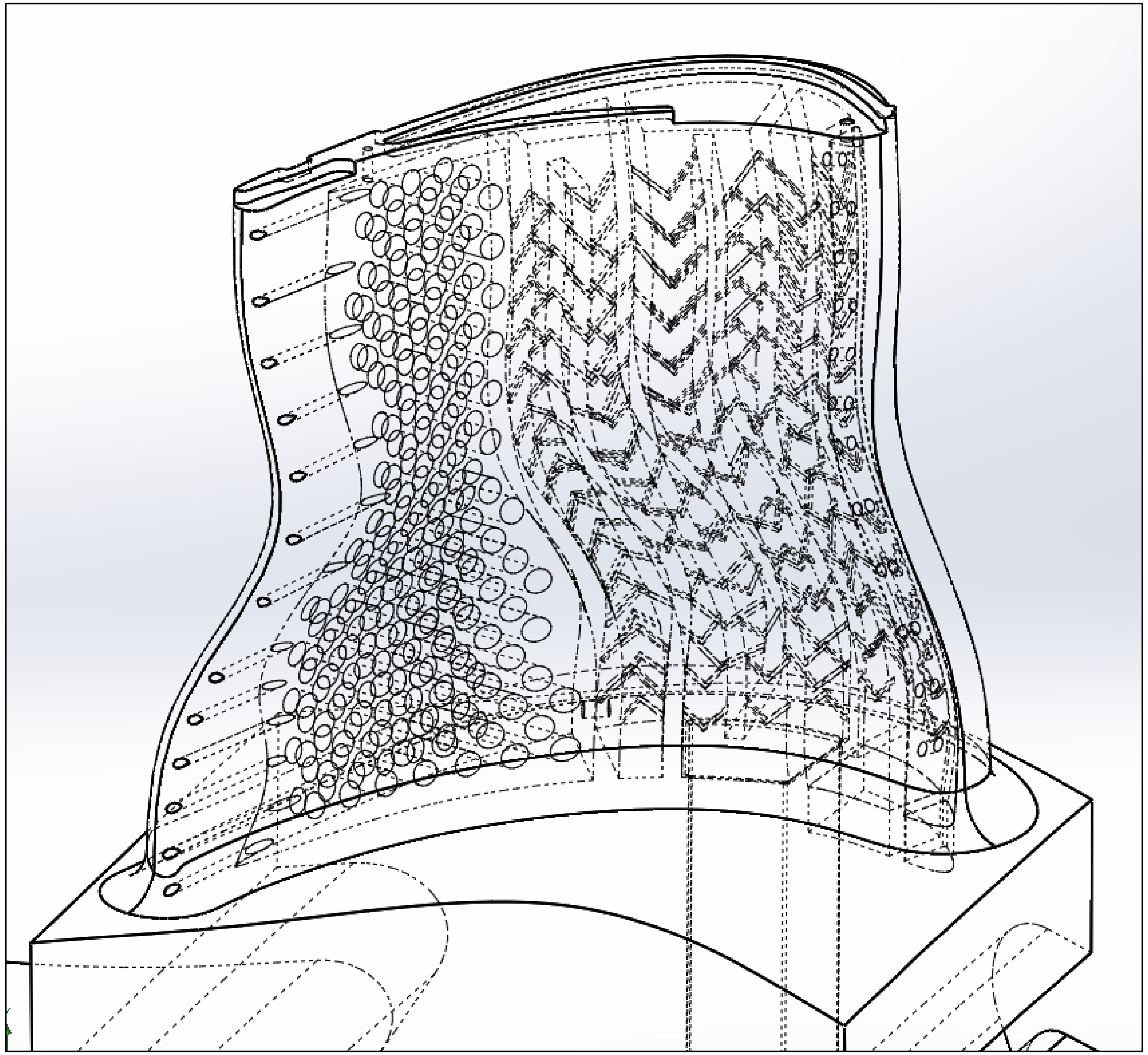




F: Elastic-Plastic (Corrected with loading factors)
Equivalent Stress - Full Assembly
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 3
12/18/2023 5

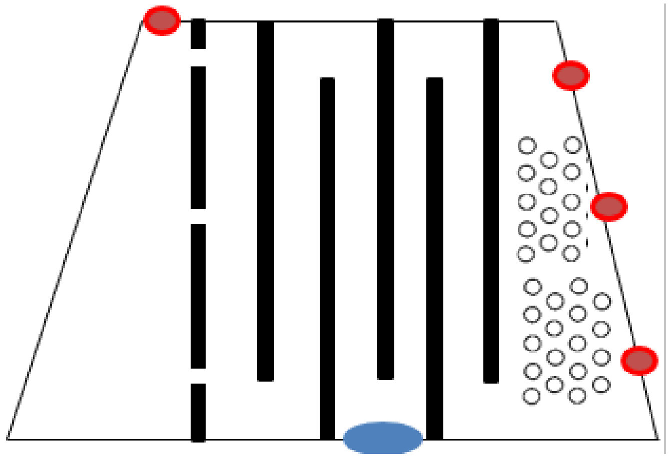
S1B Internal Cooling Design

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



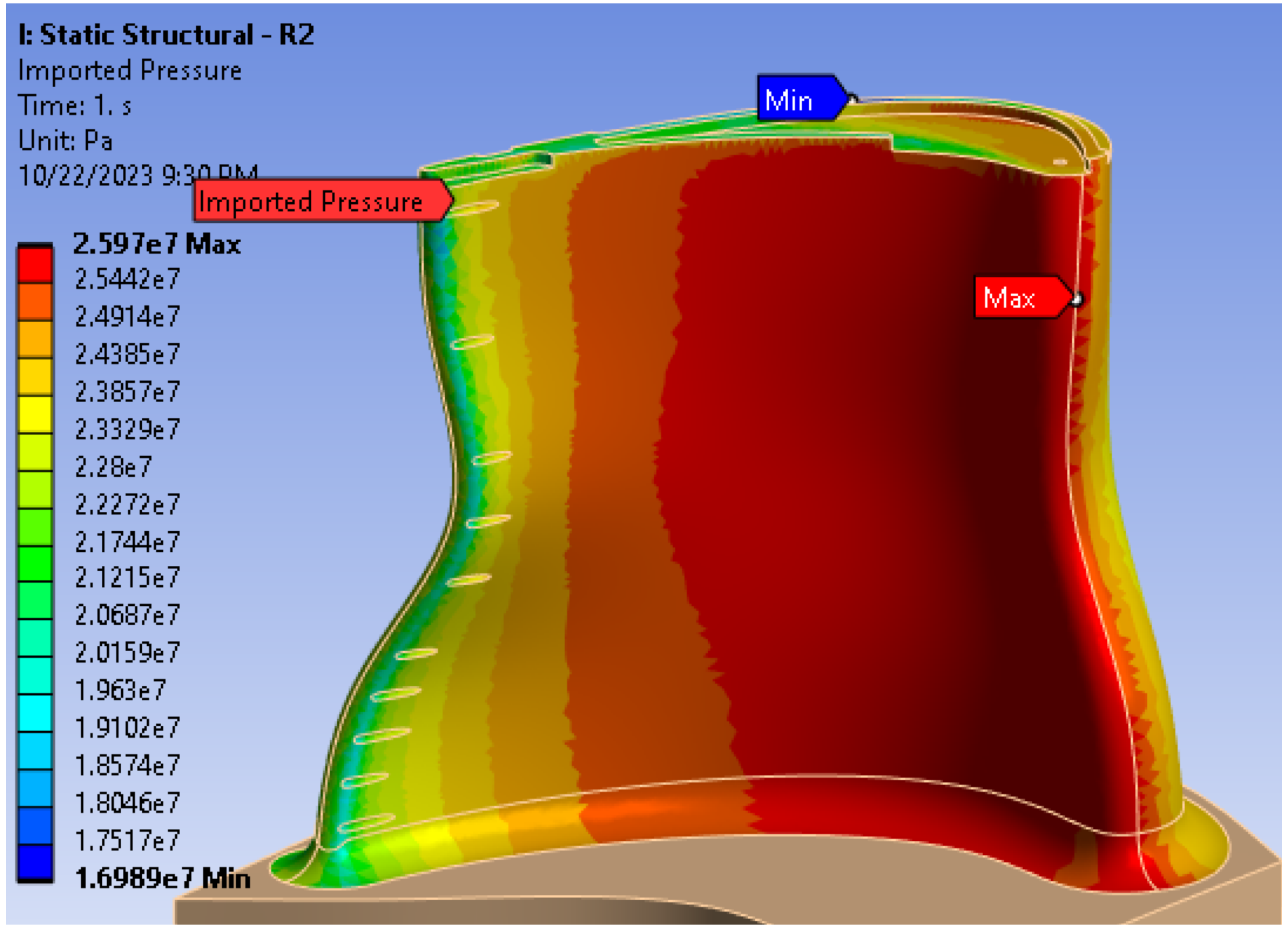
S1B thermal and hydraulic network

- Mass flow calculated from pressure differential and area at each flow ejection hole
  - Hole discharge coefficients from literature (Cd = 0.75)
  - Ribbed channels f/f0 = 10.
  - Pin fin array friction factor of 0.2 per row.
- Thermal resistance network used to estimate blade surface Temperature.
  - LE Impingement HTC determined from Chupp correlation.
  - Serpentine channel HTC from modified Gnielinski correlation with BP2 test data enhancement factor.
  - TE pin-fin array HTC from Metzger correlation
  - Thermal Barrier Coating ultimately assumed to be 0.018” thick with k = 1.25 W/m-K.

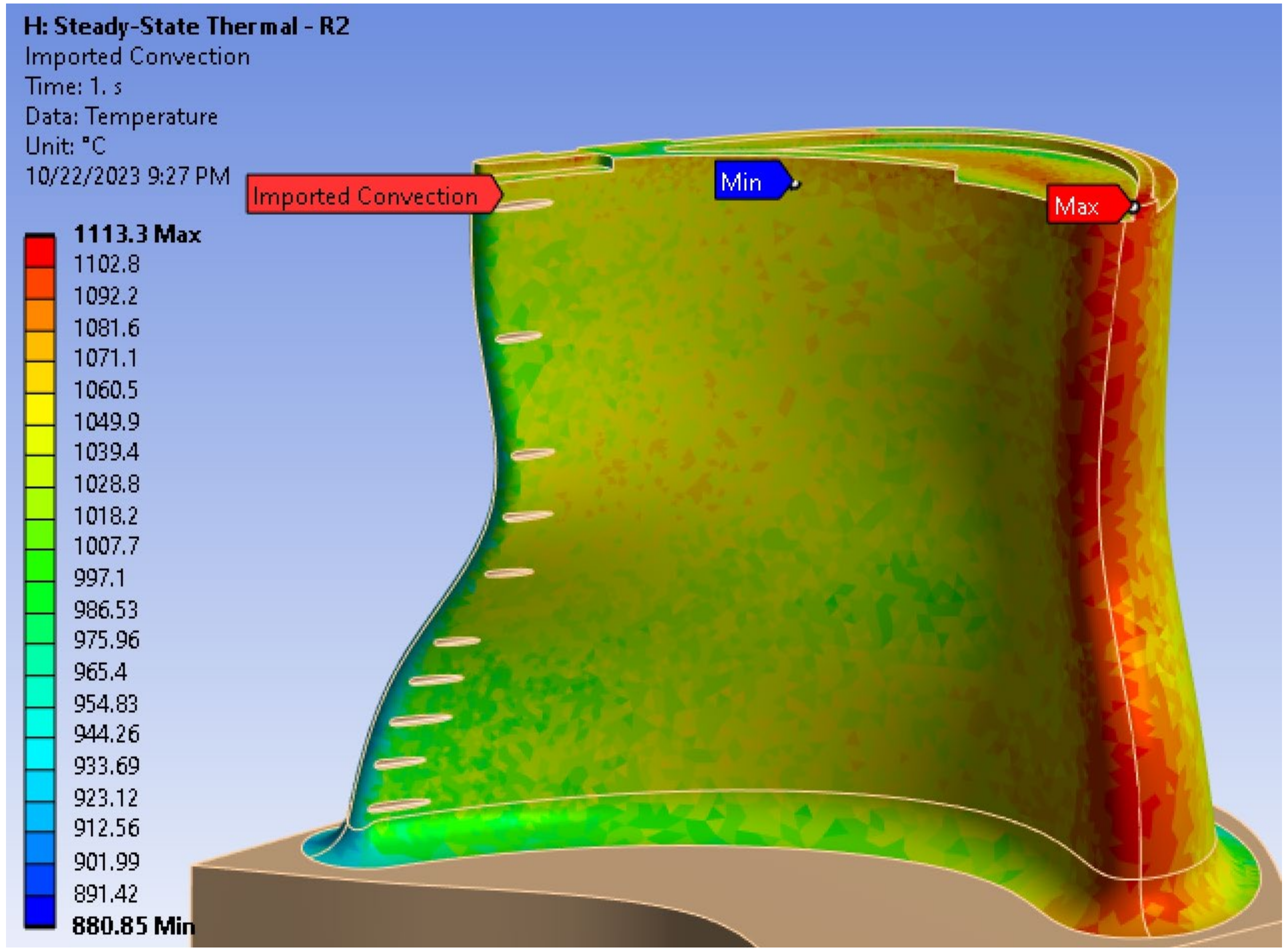


Zone	LE	Middle	TE
T - gas path (C)	1114	1089	1064
T - internal cooling (C)	526.22	445	430
R - gas path (K/W)	0.1969	0.0615	0.0438
R - tbc (K/W)	3.841	0.768	0.960
R - blade wall (K/W)	0.5780	0.1156	0.1445
R - internal cooling (K/W)	0.70	0.22	0.493
R - sum (K/W)	5.314	1.165	1.642
q (W)	110.6	552.8	385.9
T - blade outer surface (C)	**667.4**	**630.4**	**676.5**

SIB FEA – Imported Profiles

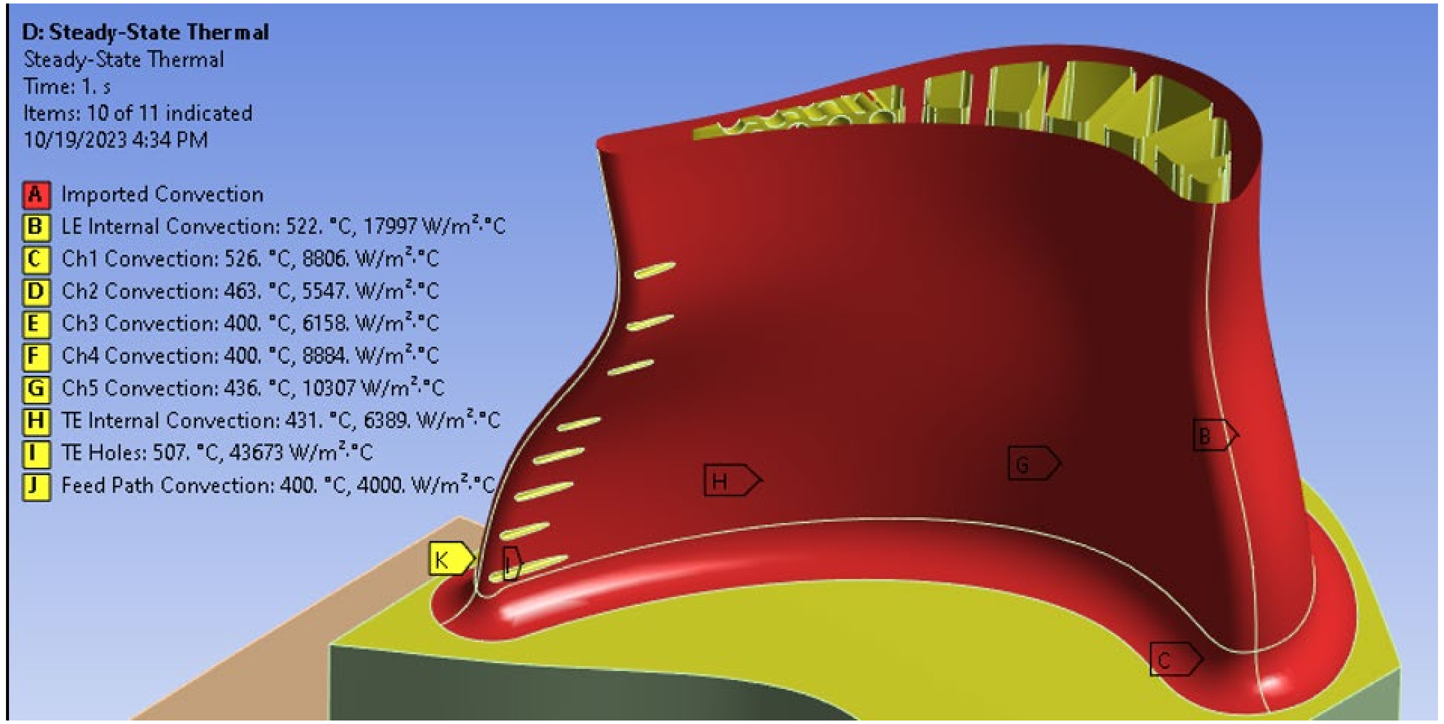


Imported pressure loading.



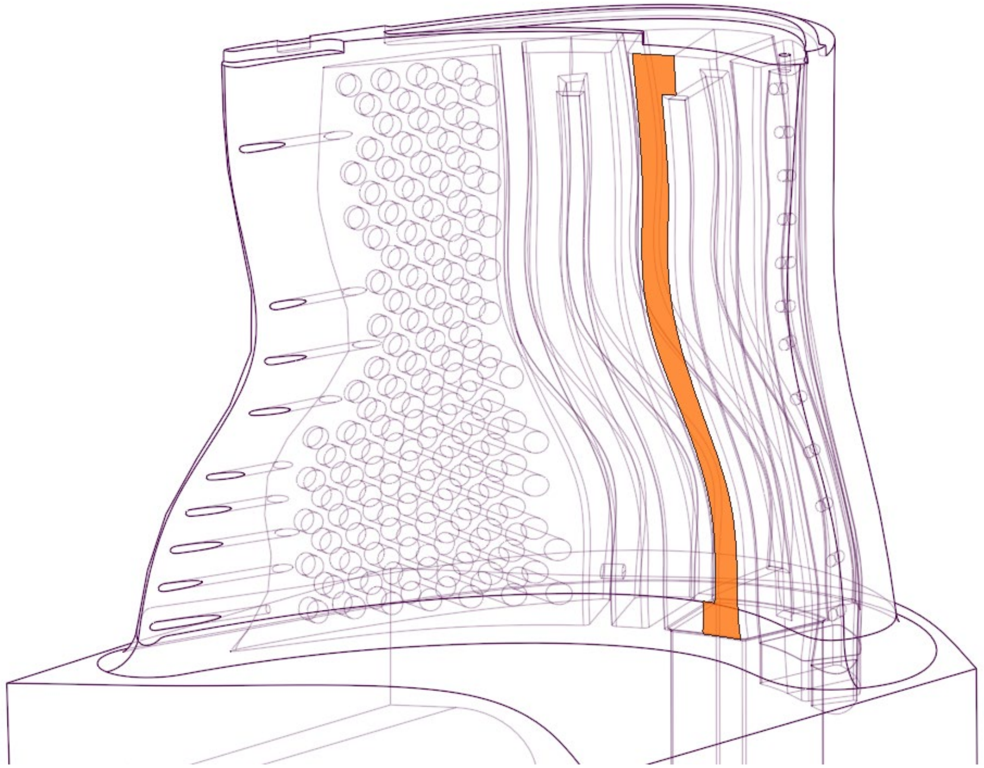
Imported convection source temperature for external heat load.

Thermal FEA Setup



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/m^2·°C
- C Ch1 Convection: 526. °C, 8806. W/m^2·°C
- D Ch2 Convection: 463. °C, 5547. W/m^2·°C
- E Ch3 Convection: 400. °C, 6158. W/m^2·°C
- F Ch4 Convection: 400. °C, 8884. W/m^2·°C
- G Ch5 Convection: 436. °C, 10307 W/m^2·°C
- H TE Internal Convection: 431. °C, 6389. W/m^2·°C
- I TE Holes: 507. °C, 43673 W/m^2·°C
- J Feed Path Convection: 400. °C, 4000. W/m^2·°C

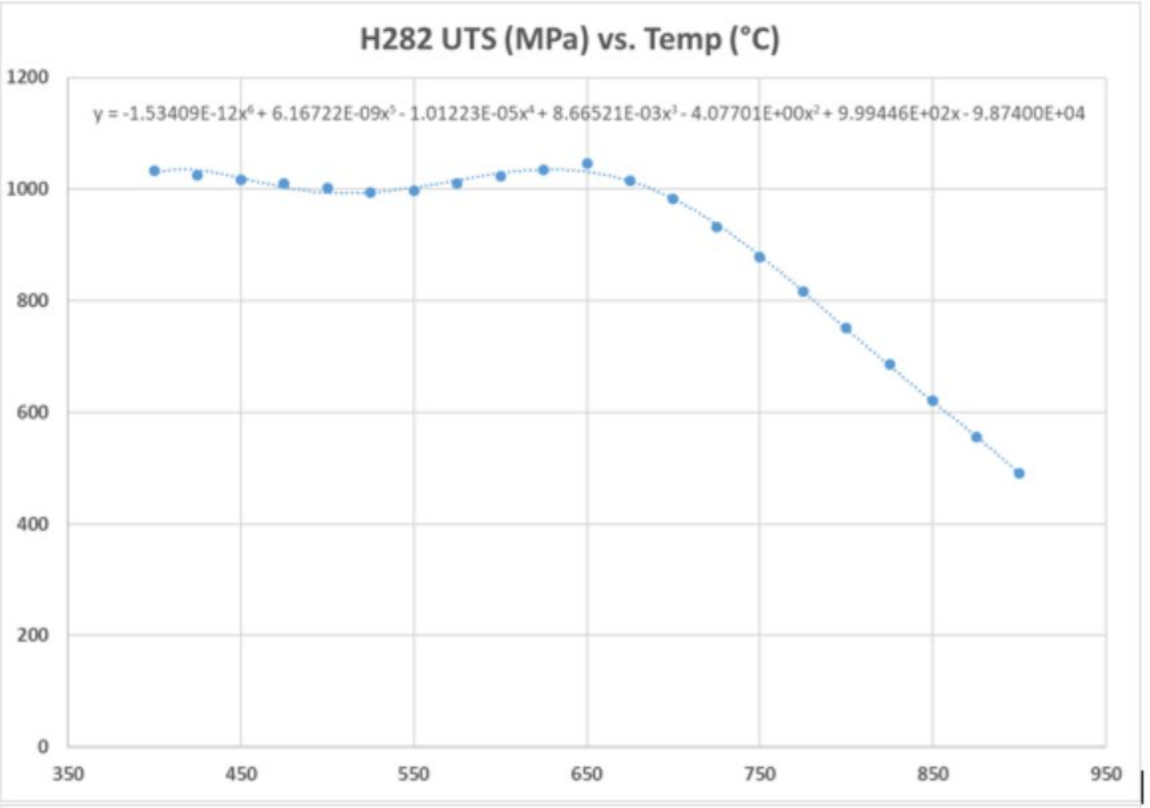


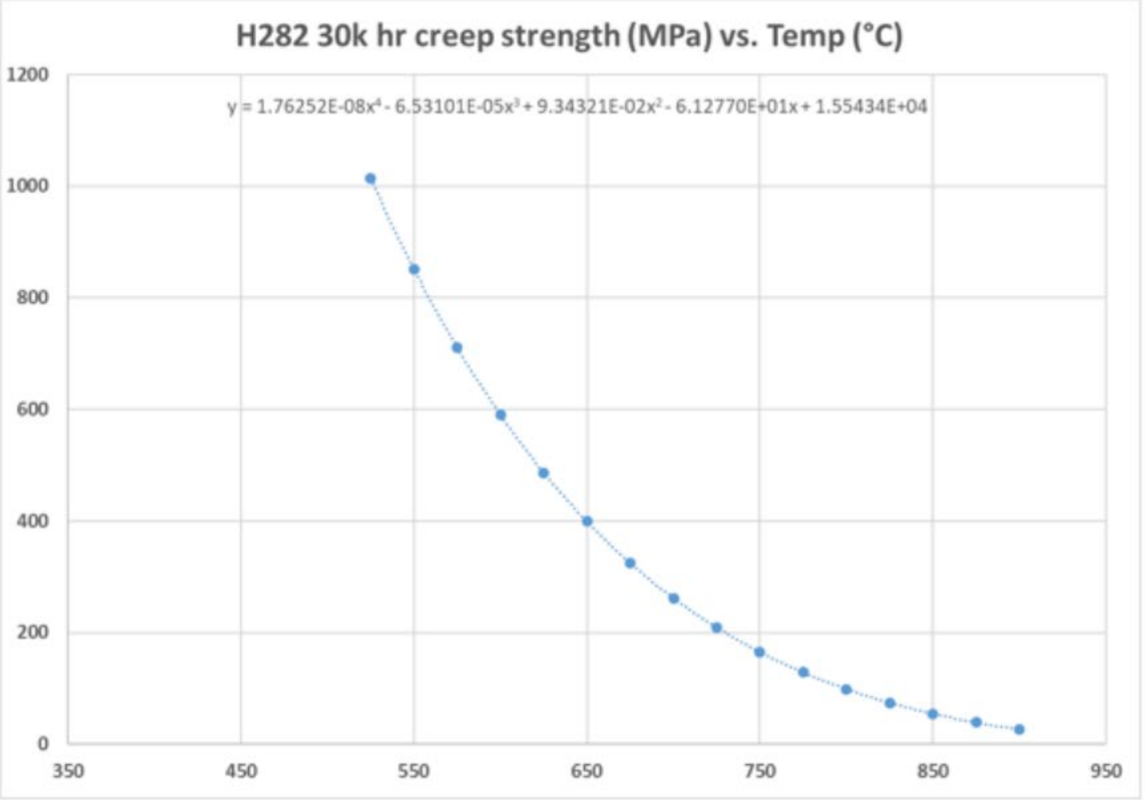
- Each internal passage is given a unique cooling CO_2 temperature and heat transfer coefficient.
- An approximate 100°C temperature rise is predicted from feed passage to LE and TE cavities.

S1B Structural Result Criteria

- Curve fits are produced for Haynes 282 UTS and 30k hour creep strength as a function of temperature.
- Result for initial evaluation:

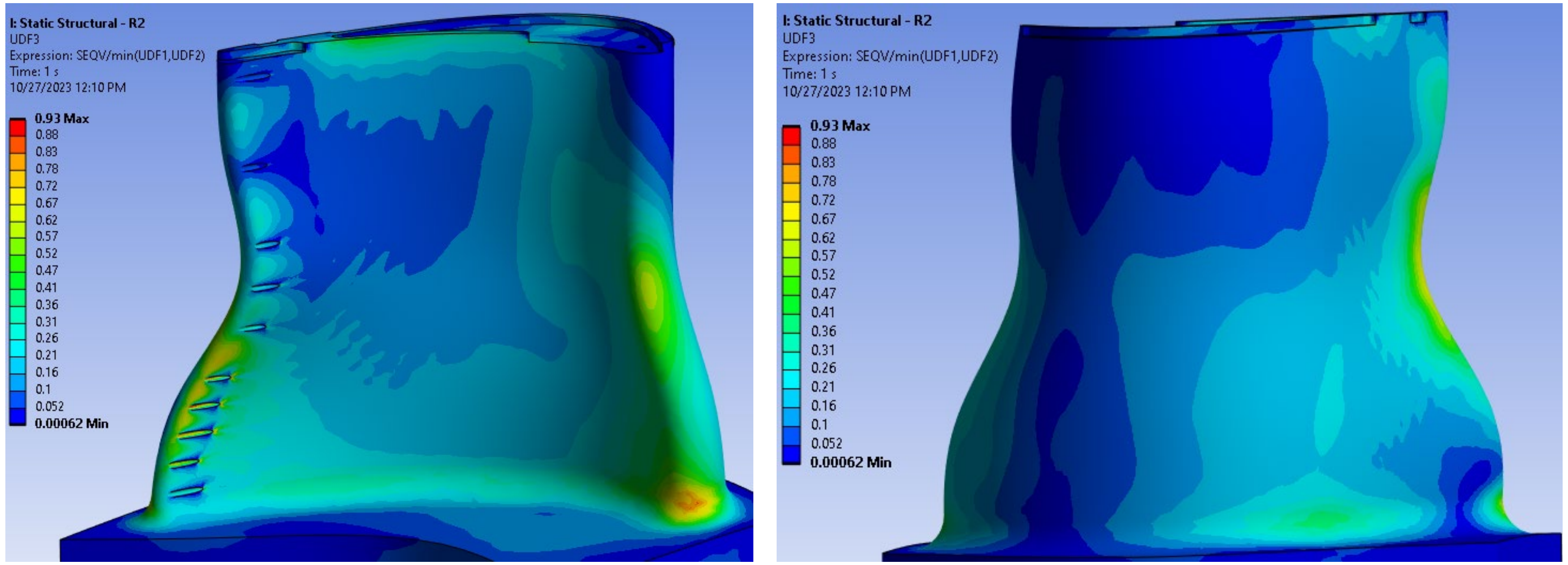
$$f = \frac{\sigma_{VM}}{\min(UTS(T), \sigma_{cr}(T))}$$



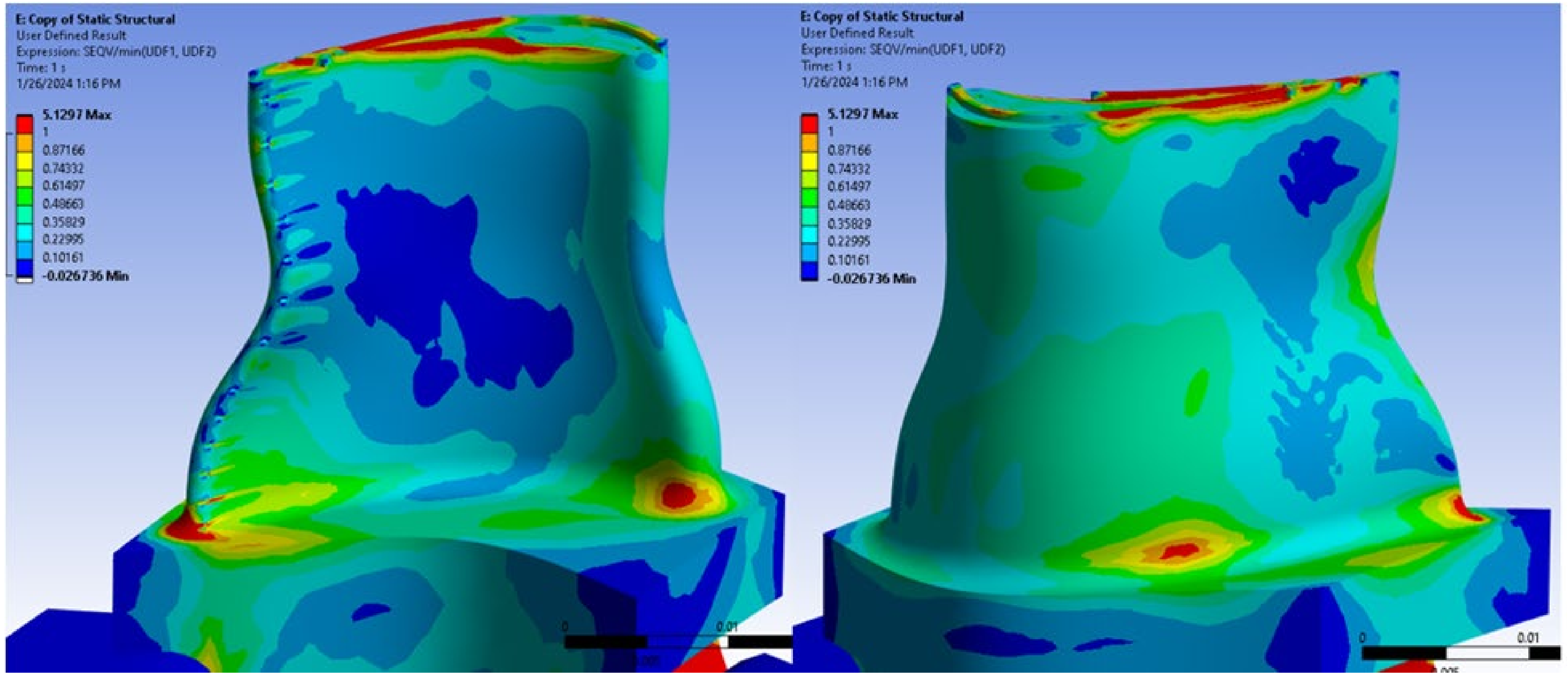


SIB FEA Result

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

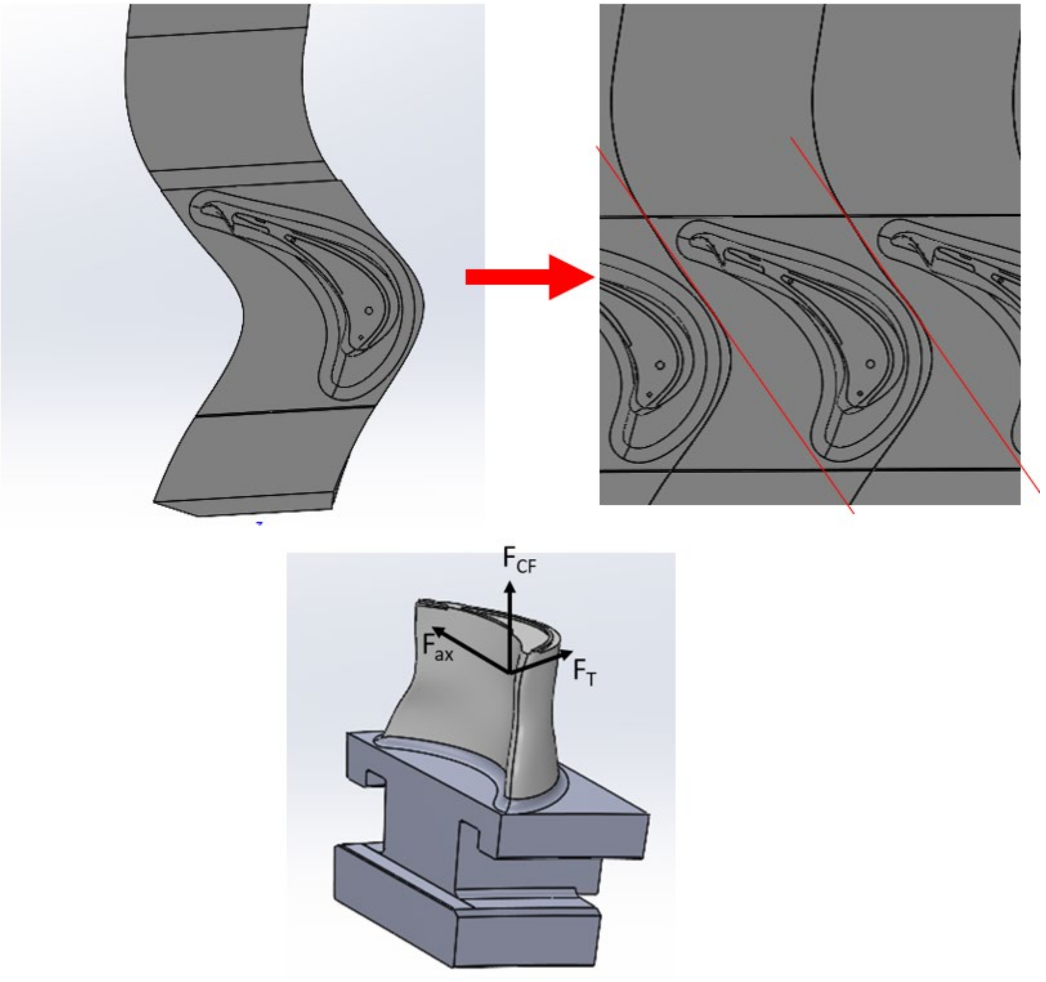


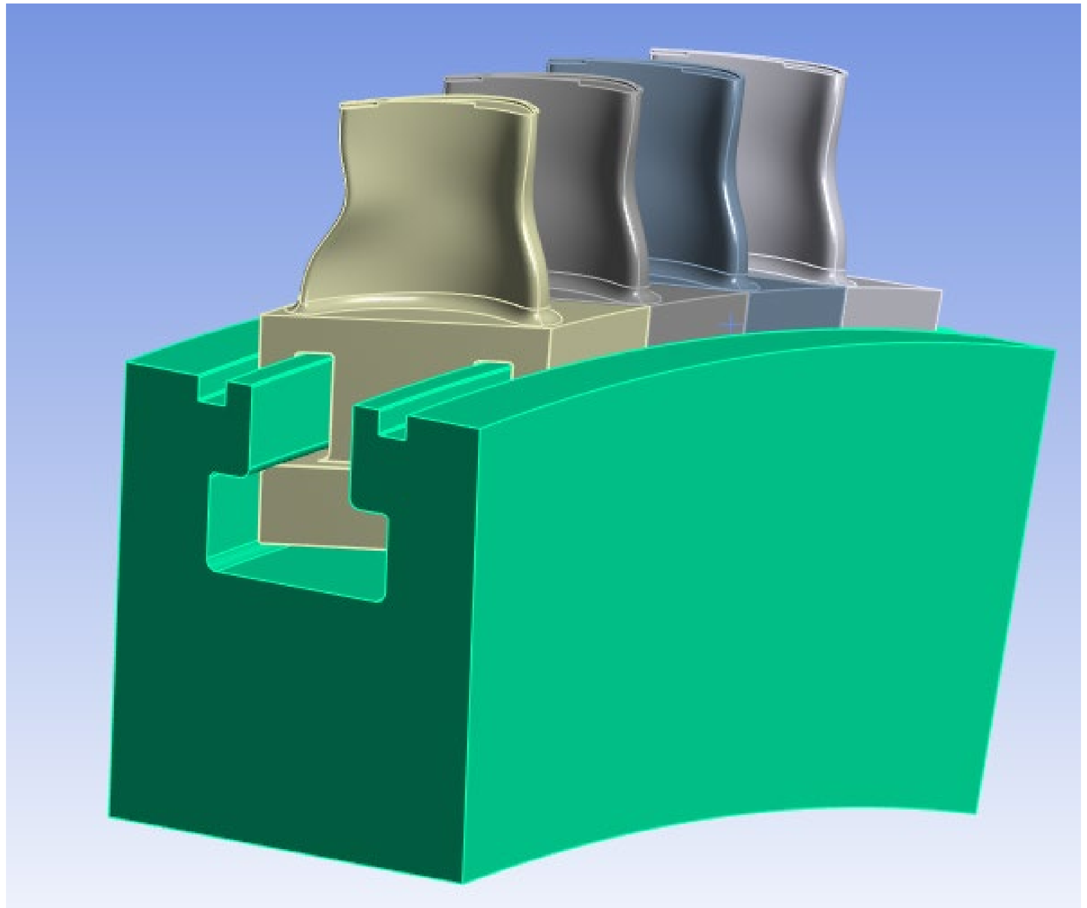
- Pressure loading, centrifugal loading.



- Pressure loading, centrifugal loading, thermal expansion effects.

Blade Root Design



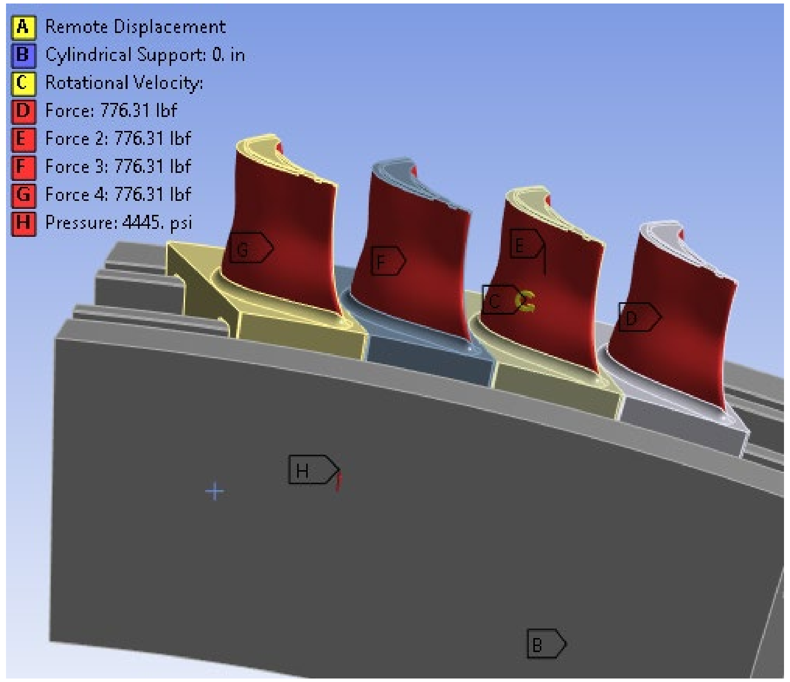


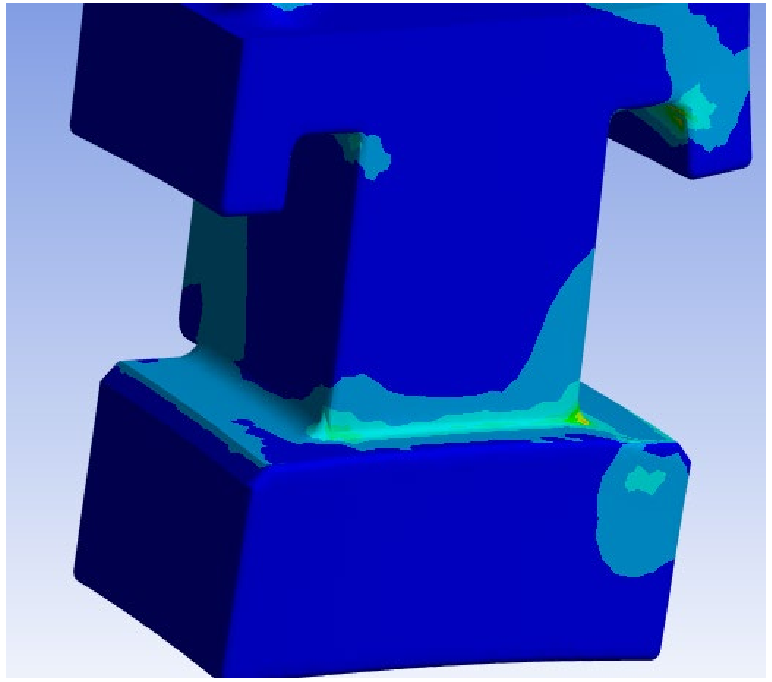
- Parallel T-root chosen for monolithic rotor based on literature study.
- Sidestep on base of T-root allows for blades to load off of each other.

Blade Root Structural Evaluation

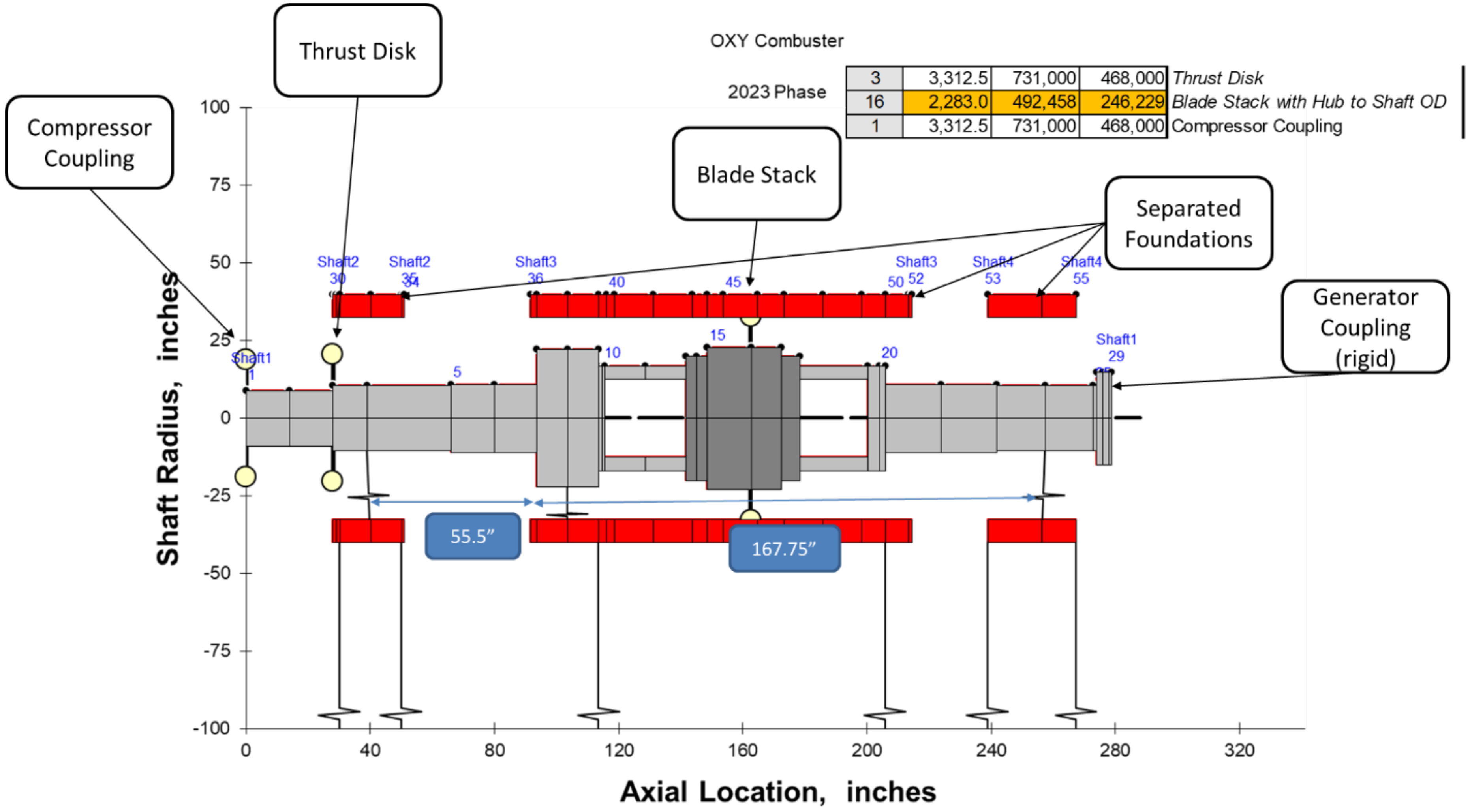
- Boundary Conditions
  - Blade Loading From GE
  - Run with Solid Blade – H282
  - 1/8" Cooling Port

		Rotor Thrust		**Tangential Force**	
	Count	Total	Per Blade	Total	Per Blade
	#	lbf	lbf	lbf	lbf
Blade 1	142	82,351	579.9	73,259	515.9
Blade 2	142	87,750	618.0	74,212	522.6
Blade 3	142	81,806	576.1	75,217	529.7
Blade 4	126	70,228	557.4	74,498	591.3
Blade 5	126	55,424	439.9	72,064	571.9
Blade 6	126	37,759	299.7	69,903	554.8
total		415,319			





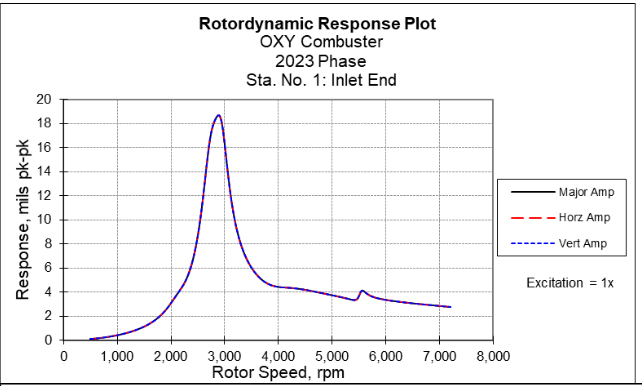
Rotordynamics Model

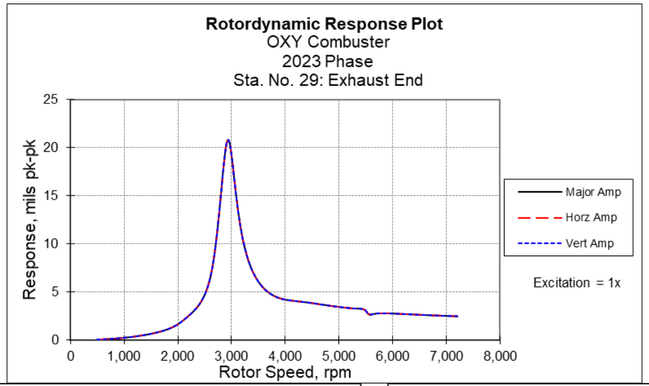


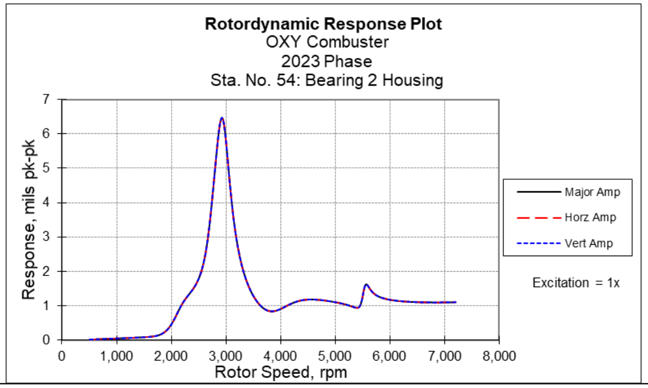
3	3,312.5	731,000	468,000	*Thrust Disk*
16	2,283.0	492,458	246,229	*Blade Stack with Hub to Shaft OD*
1	3,312.5	731,000	468,000	Compressor Coupling

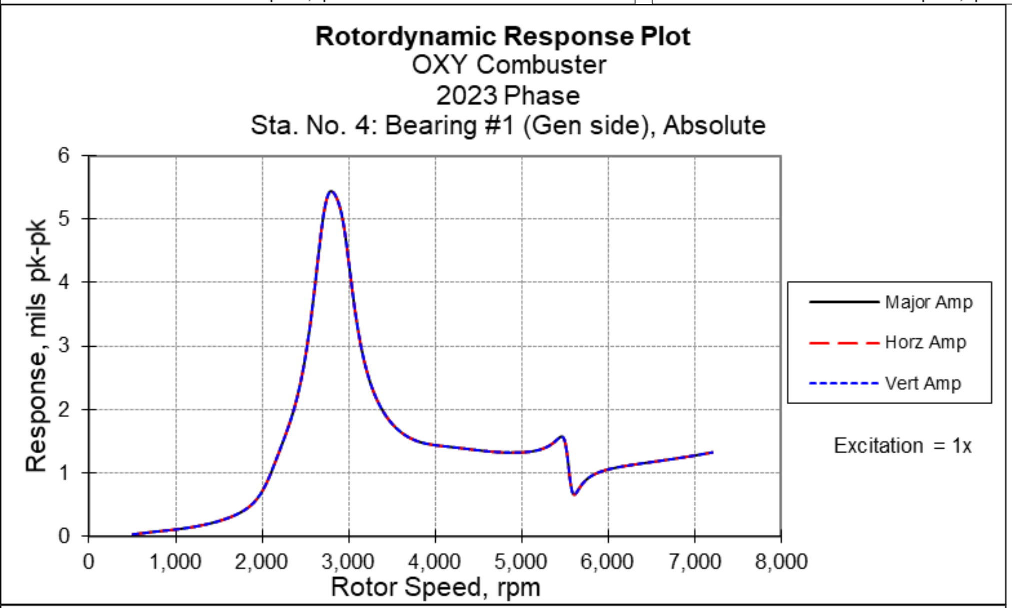
- Coupling and bearing specifications received from vendors.

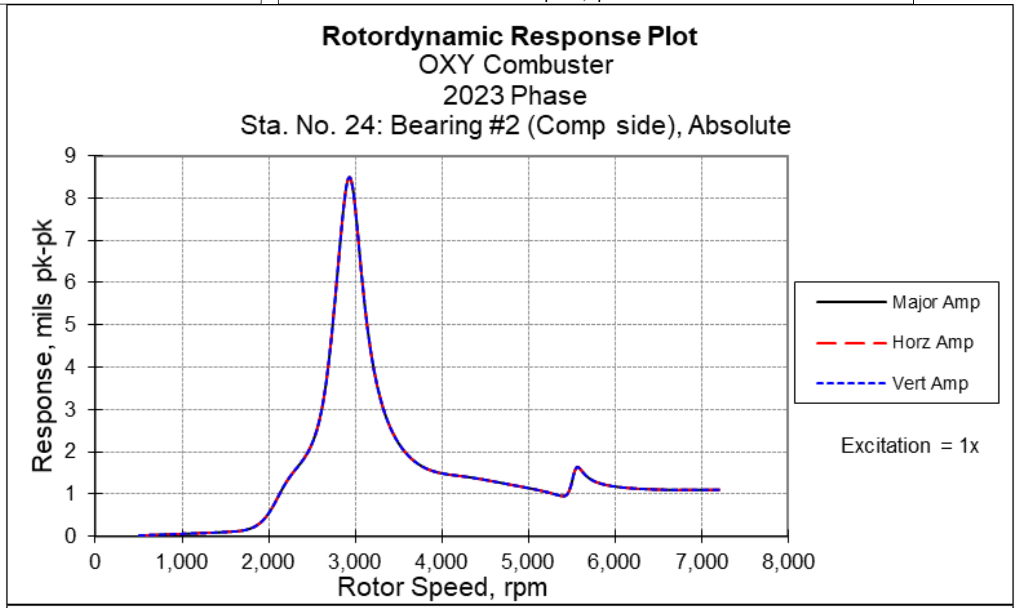
Rotordynamics Response Plots

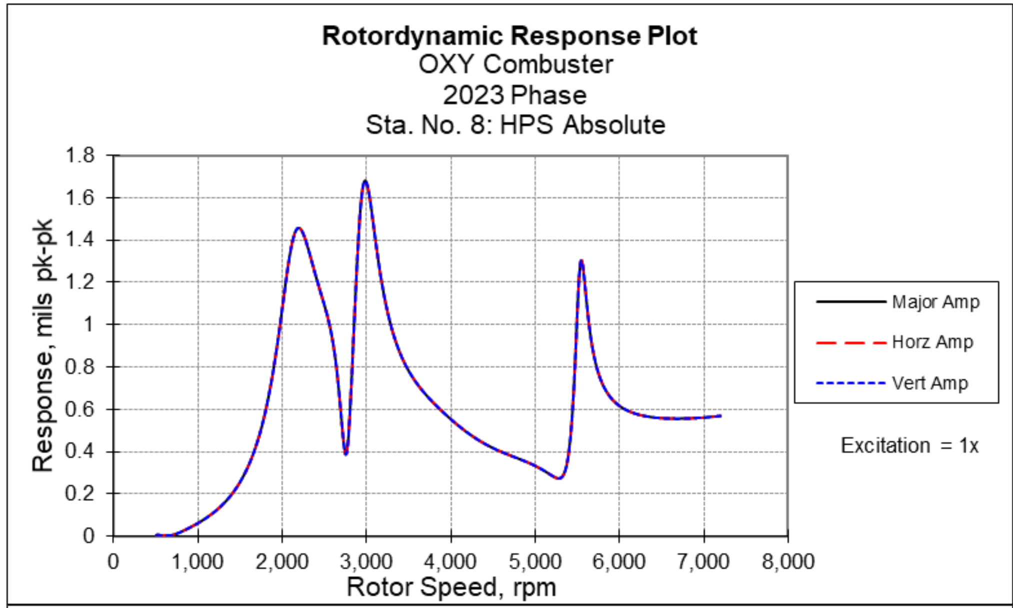


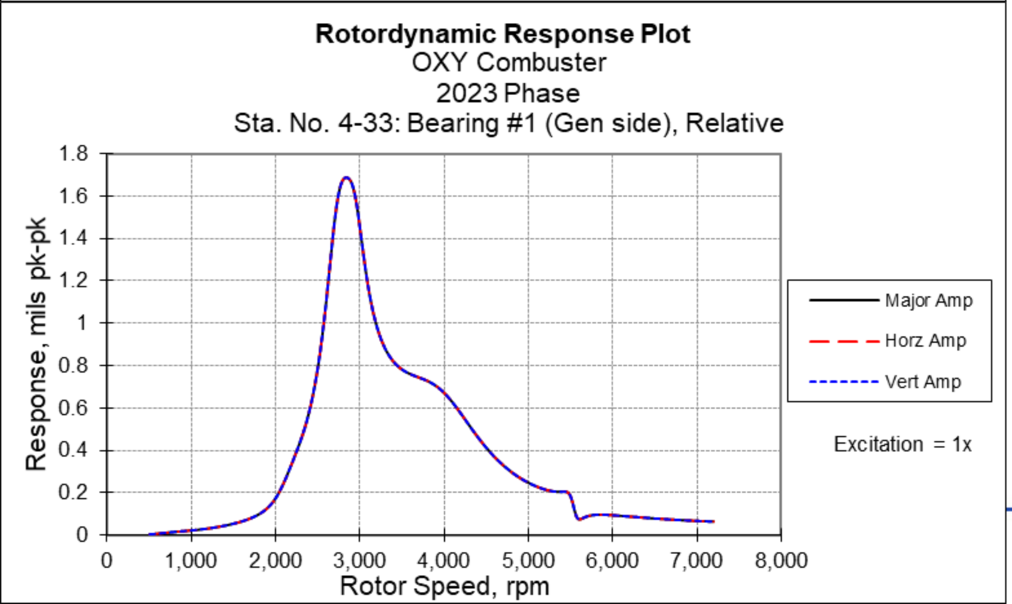


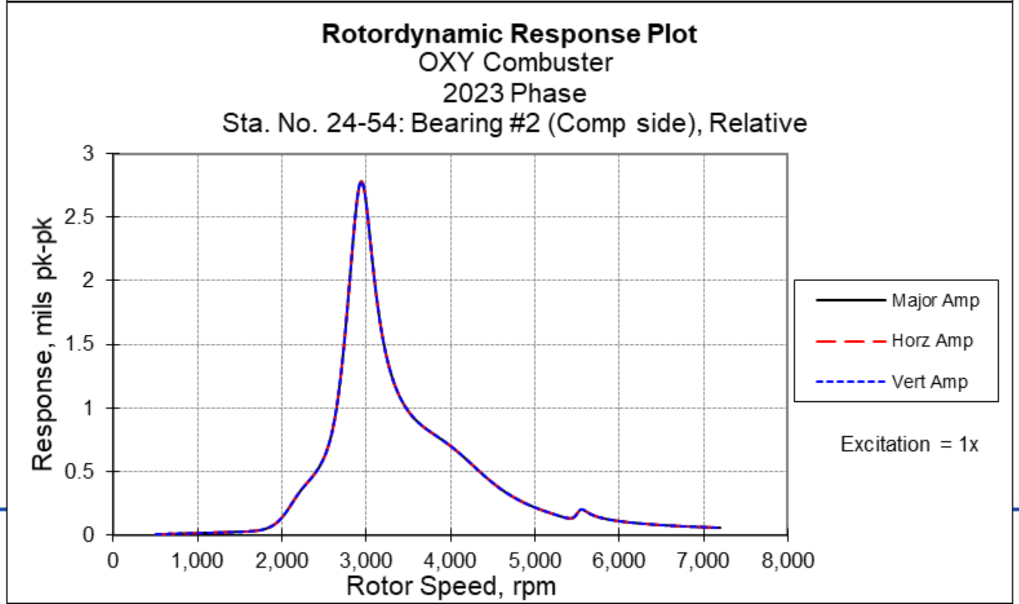


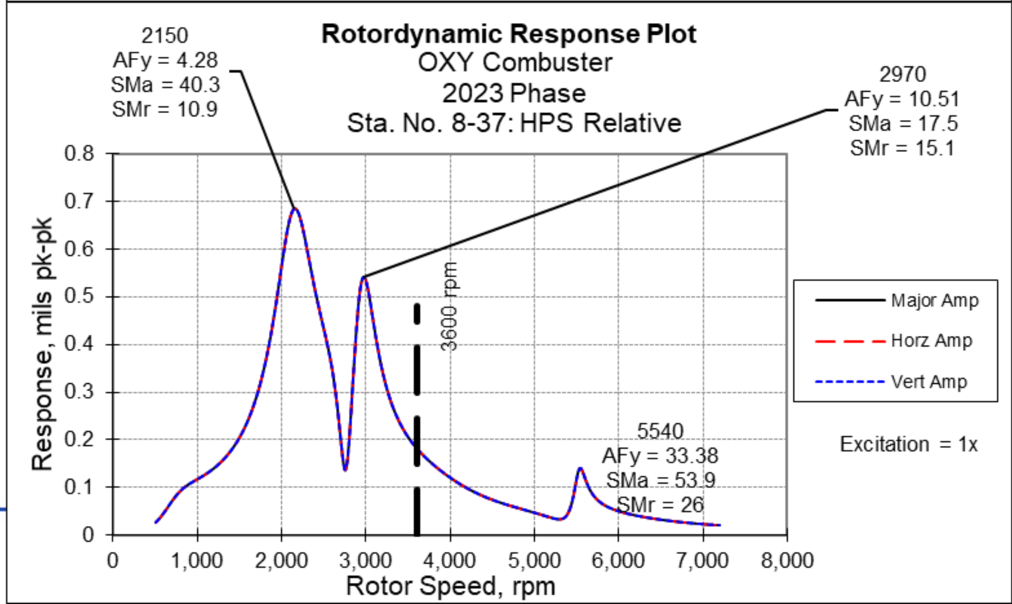




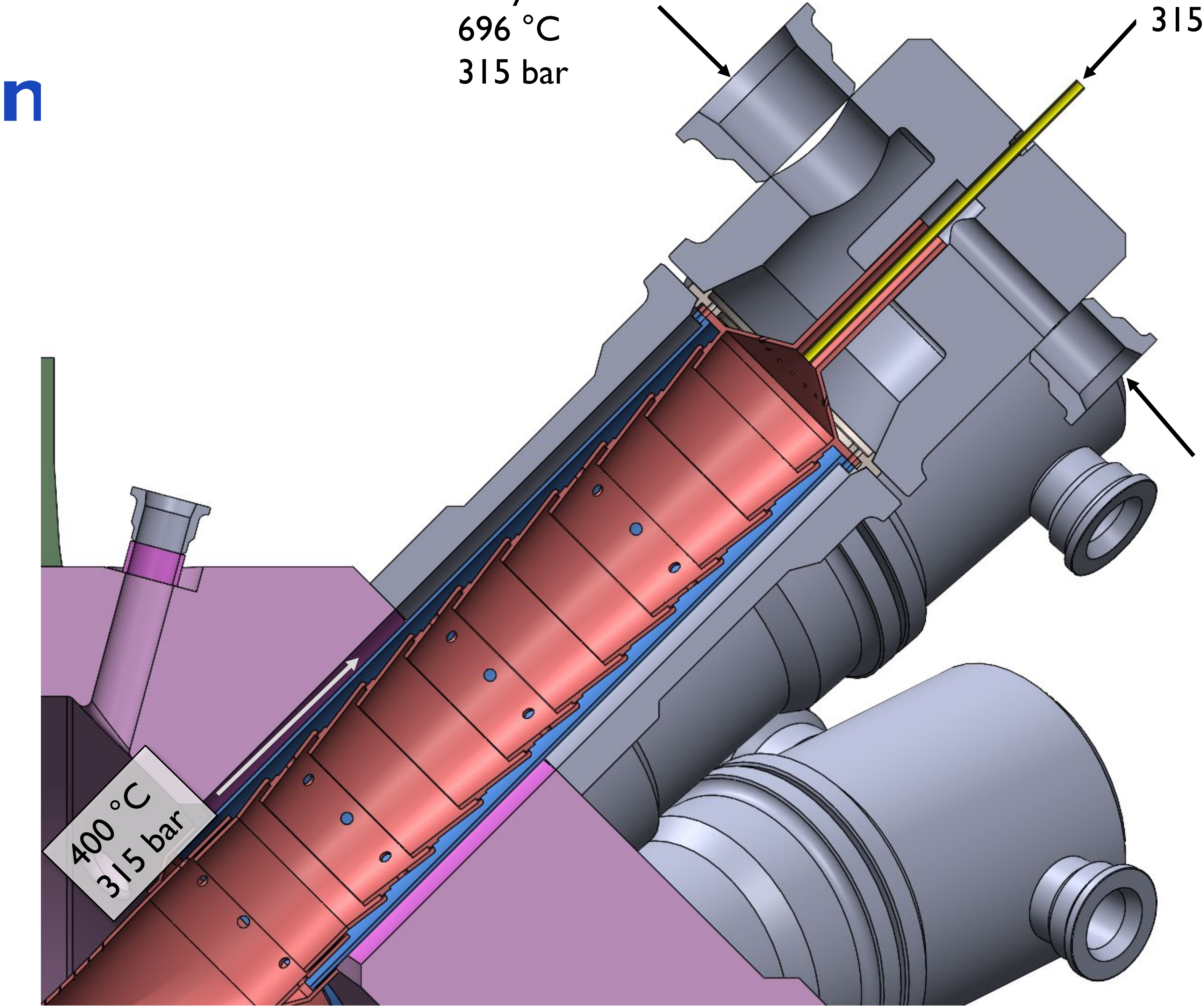








Combustor Flow Diagran



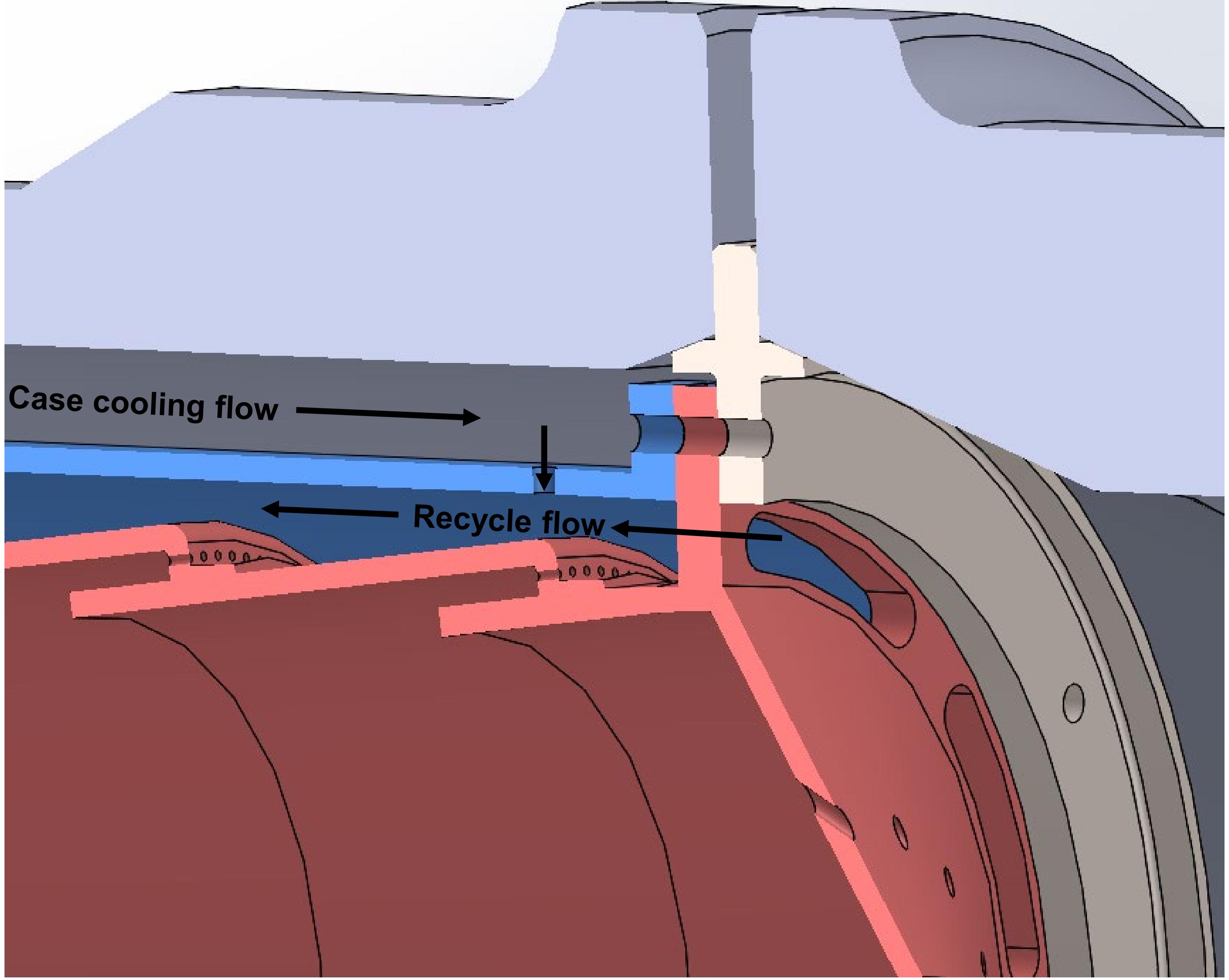
Recycle Flow
696 °C
315 bar

Fuel (2.45CO:H2)
315 bar

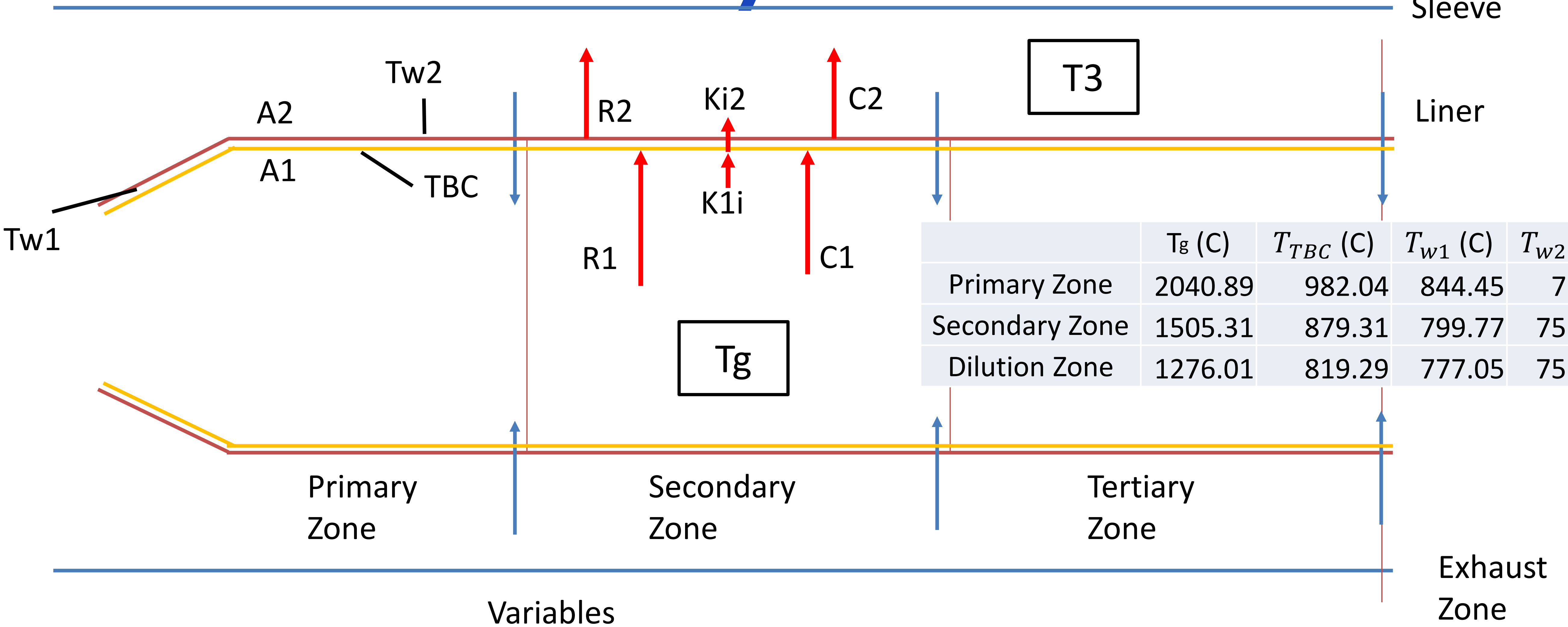
Oxidizer
696 °C
315 bar

Combustor thermal management

- Cooling flow jackets the combustor housing nozzle to extend lifetime of nozzle welded to combustor housing.
- Liner thermal analysis underway to modify geometry and determine TBC requirements for 30,000 hr. target lifetime.



Liner Thermal Analysis



	Tg (C)	T_{TBC} (C)	T_{w1} (C)	T_{w2} (C)	T3 (C)
Primary Zone	2040.89	982.04	844.45	764.8	695.8
Secondary Zone	1505.31	879.31	799.77	752.72	696.9
Dilution Zone	1276.01	819.29	777.05	751.83	698.12

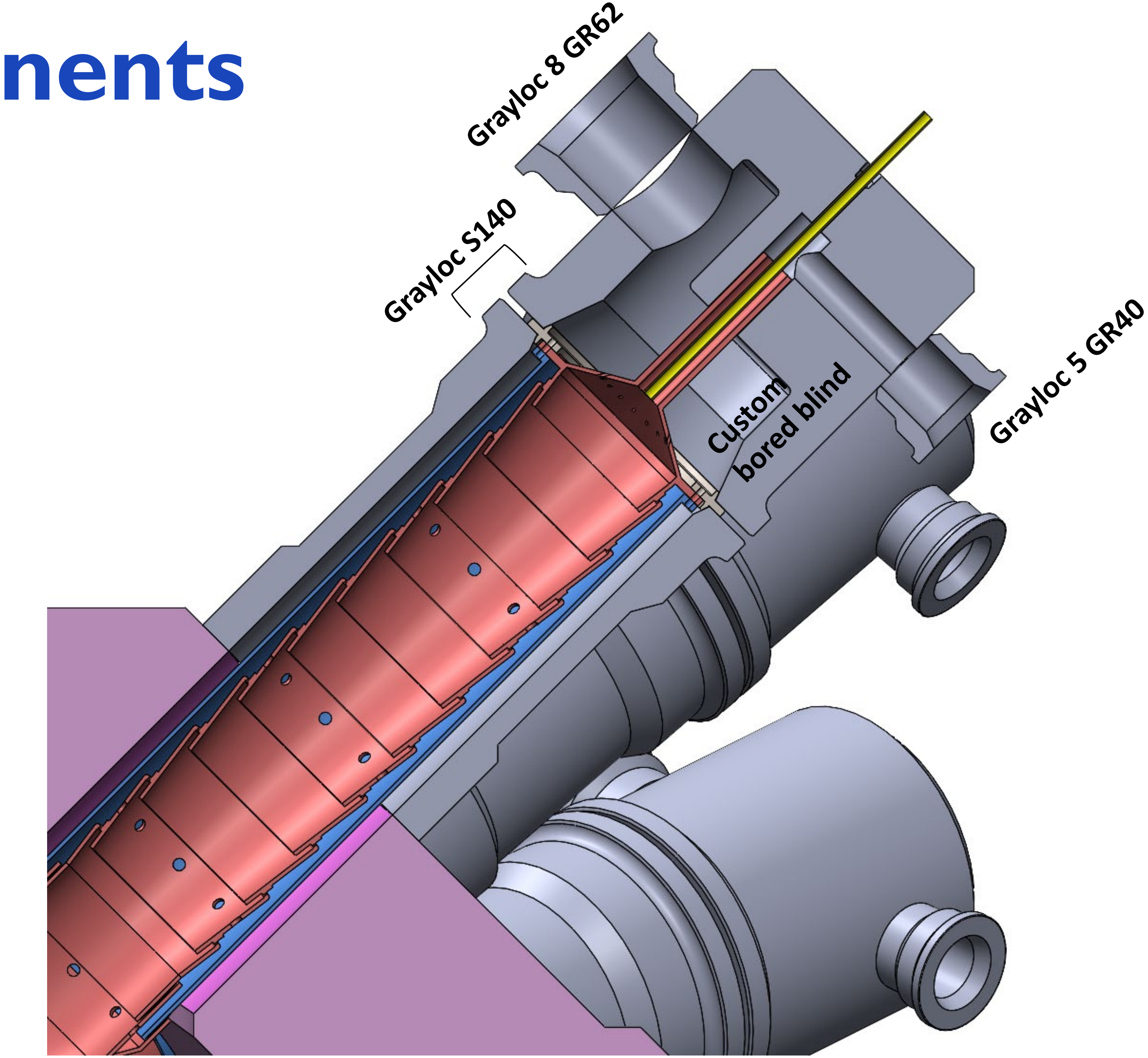
Variables

Tg = Primary flow gas temp (K)
Tw1 = liner wall inside temp (K)
Tw2 = liner wall outside temp (K)
T3 = recycle flow gas temp (K)
A1&A2 = Inside/Outside Liner Area (m2)

R1 =radiation heat flux from flame to TBC (W/m2)
C1= convective heat flux from flame to TBC (W/m2)
R2= radiation heat flux from liner wall to recycle flow (W/m2)
C2 = convective heat flux from liner wall to recycle flow (W/m2)
K1i/Ki2 = conduction heat flux through TBC (W/m2)

Combustor Components

- Recycle flow temperature and pressure (696 °C, 315 bar) mandates the use of nickel alloy (H282) for Grayloc clamp connectors and blind. ANSI flanges aren't an option.
- A remaining challenge to be met is the orientation of nozzles to simplify the required piping and manifolds.



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?