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

University Turbine Systems Research - Project Review Meeting

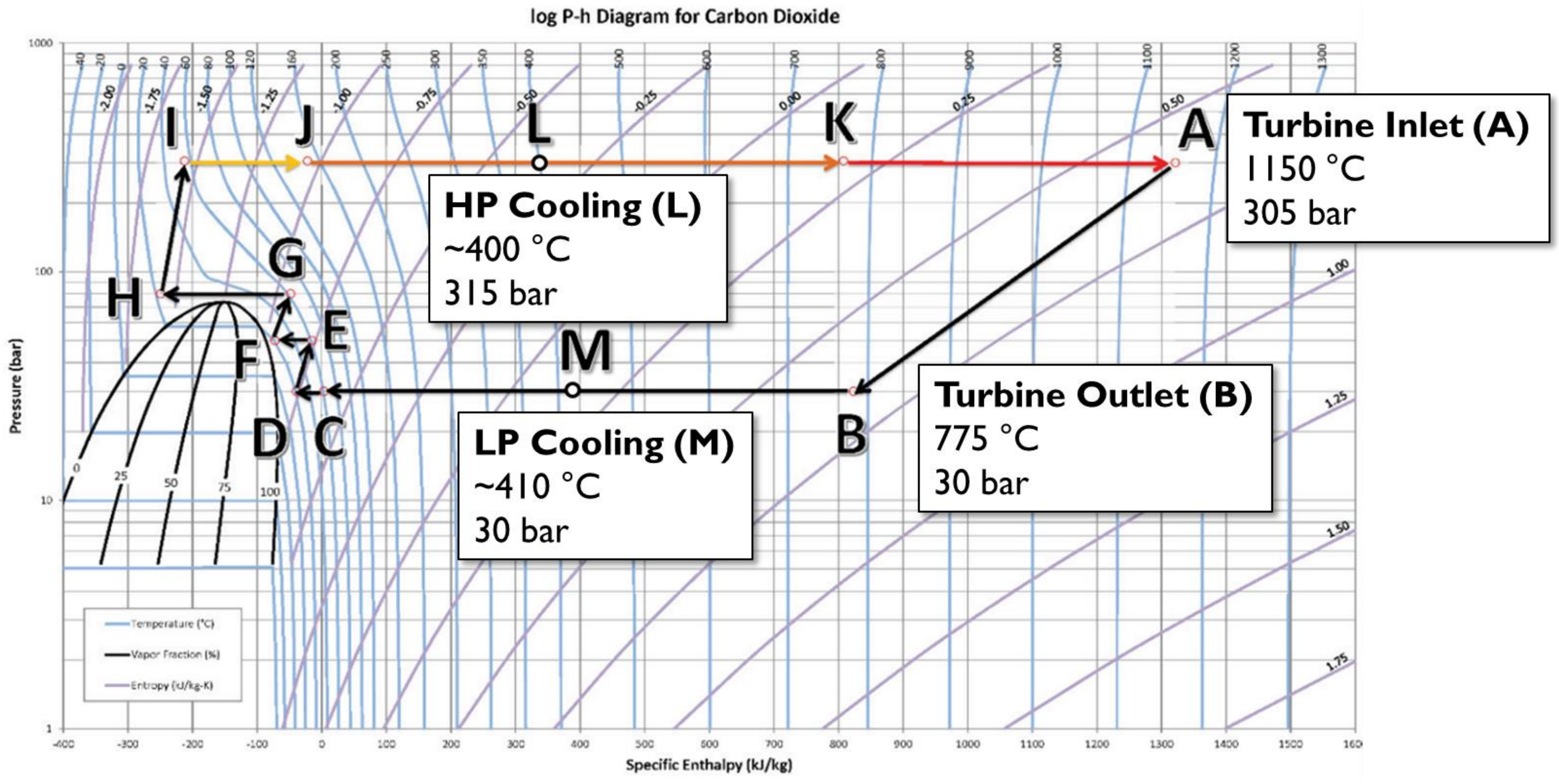
DE-FE0031929

November 1, 2023

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

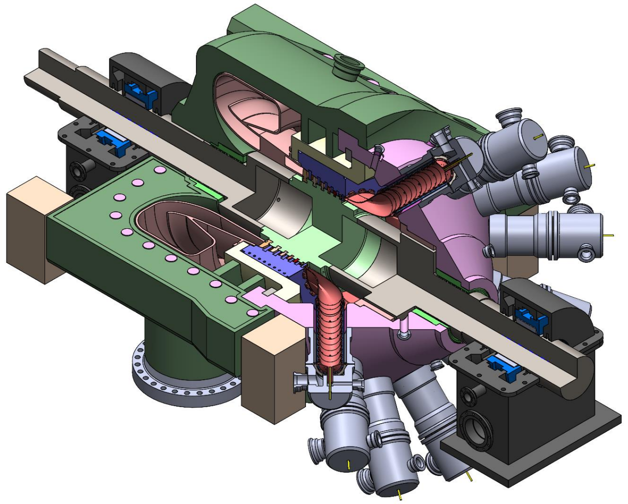
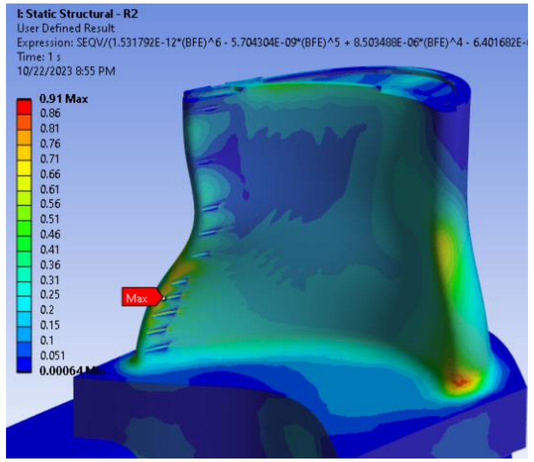
- Main Objective: Develop a detailed design for a sCO_2 direct fired oxy-fuel turbine for utility scale (300 MWe) utilizing a coal syngas fuel, with the ability to be co-fired with natural gas.
- Operation in an Allam-Fetvedt cycle targets near zero emissions, while targeting 43% LHV system efficiency.
- The density and heat transfer properties of sCO_2 can take advantage of compact turbomachinery and effective thermal management.

Turbine conditions

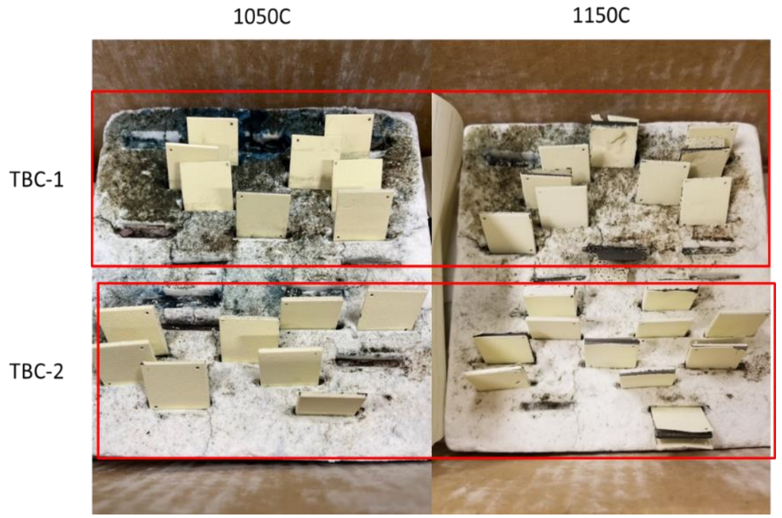


- How does this compare to steam and gas turbines?
  - Steam (AUSC): 330 bar, 670°C (Source: GE Steam Power)
  - Gas Turbine: 23 bar, 1430°C (Source: GE H-class)

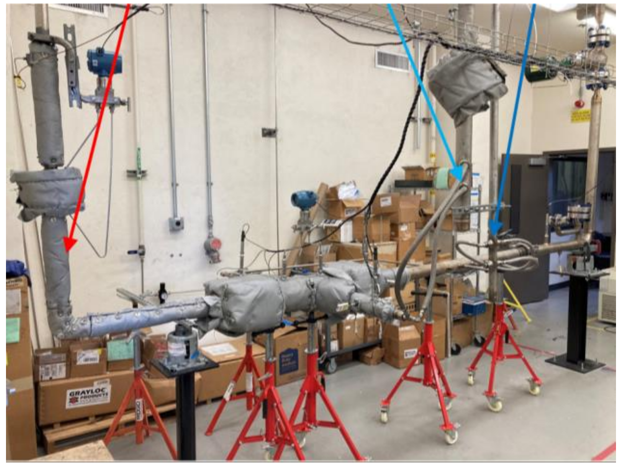
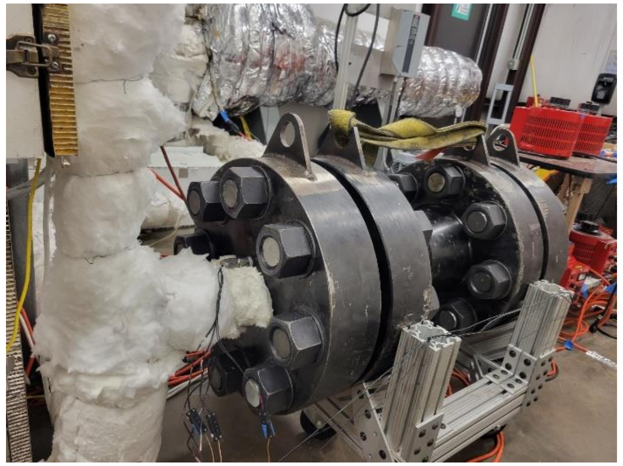
Project components

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.

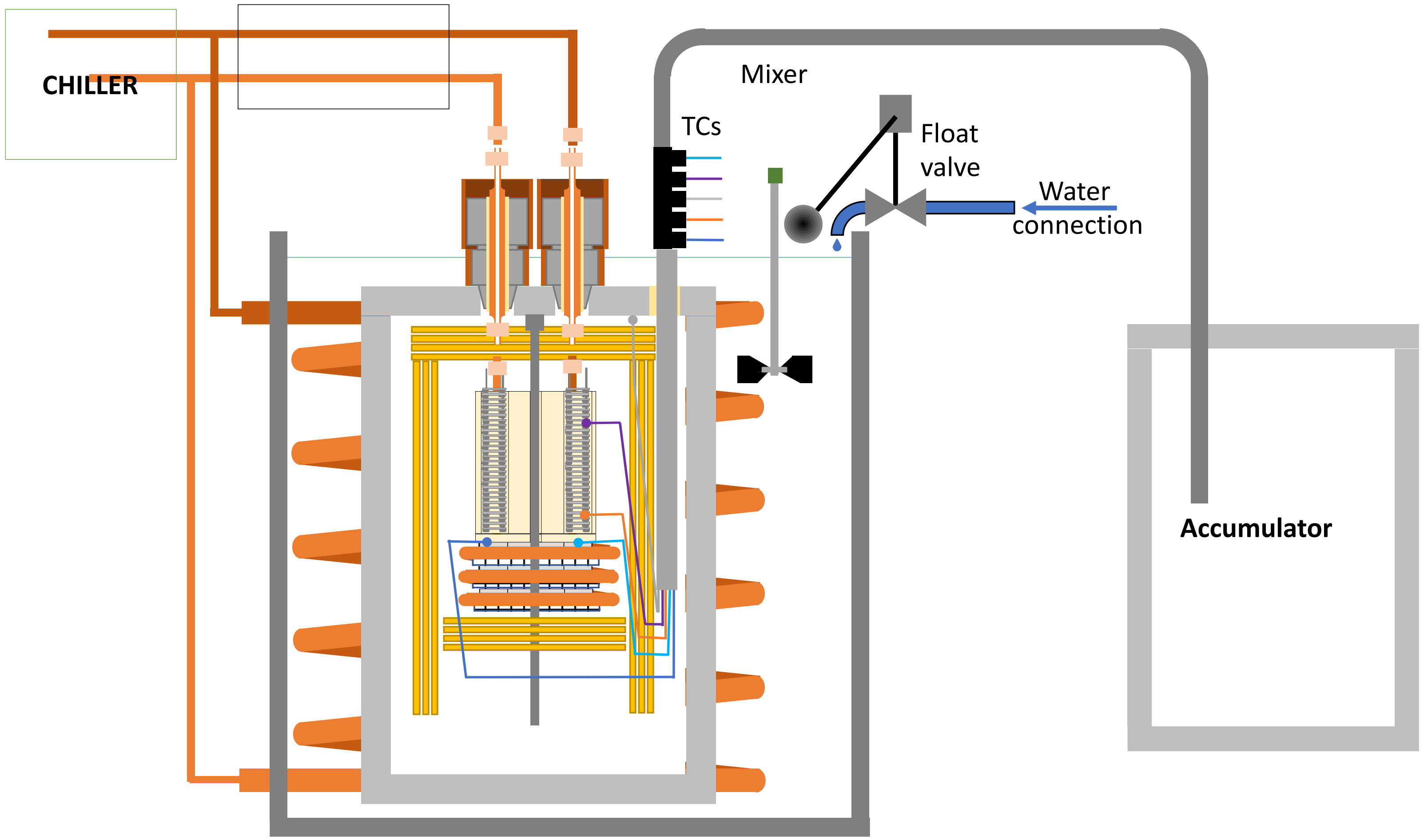
8 RIVERS — Thermodynamic cycle model.

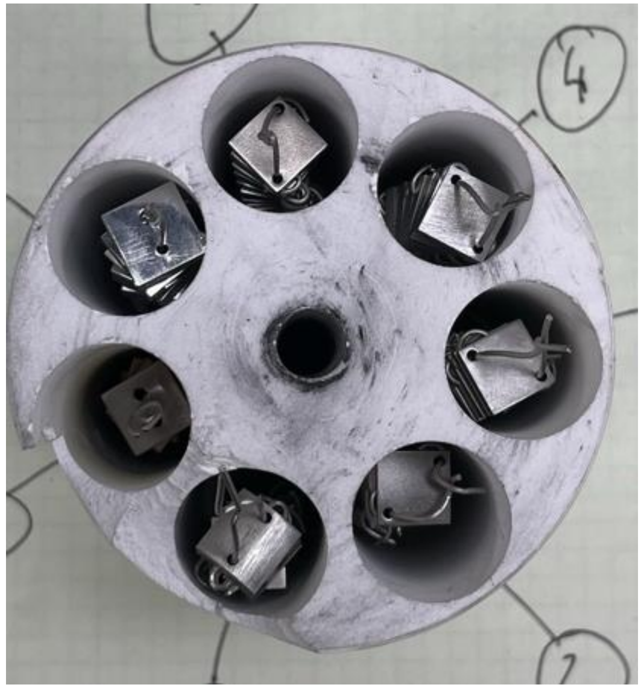
EPRI — Technoeconomic study.

Air Liquide — Oxy-combustor development and analysis.

Materials Testing

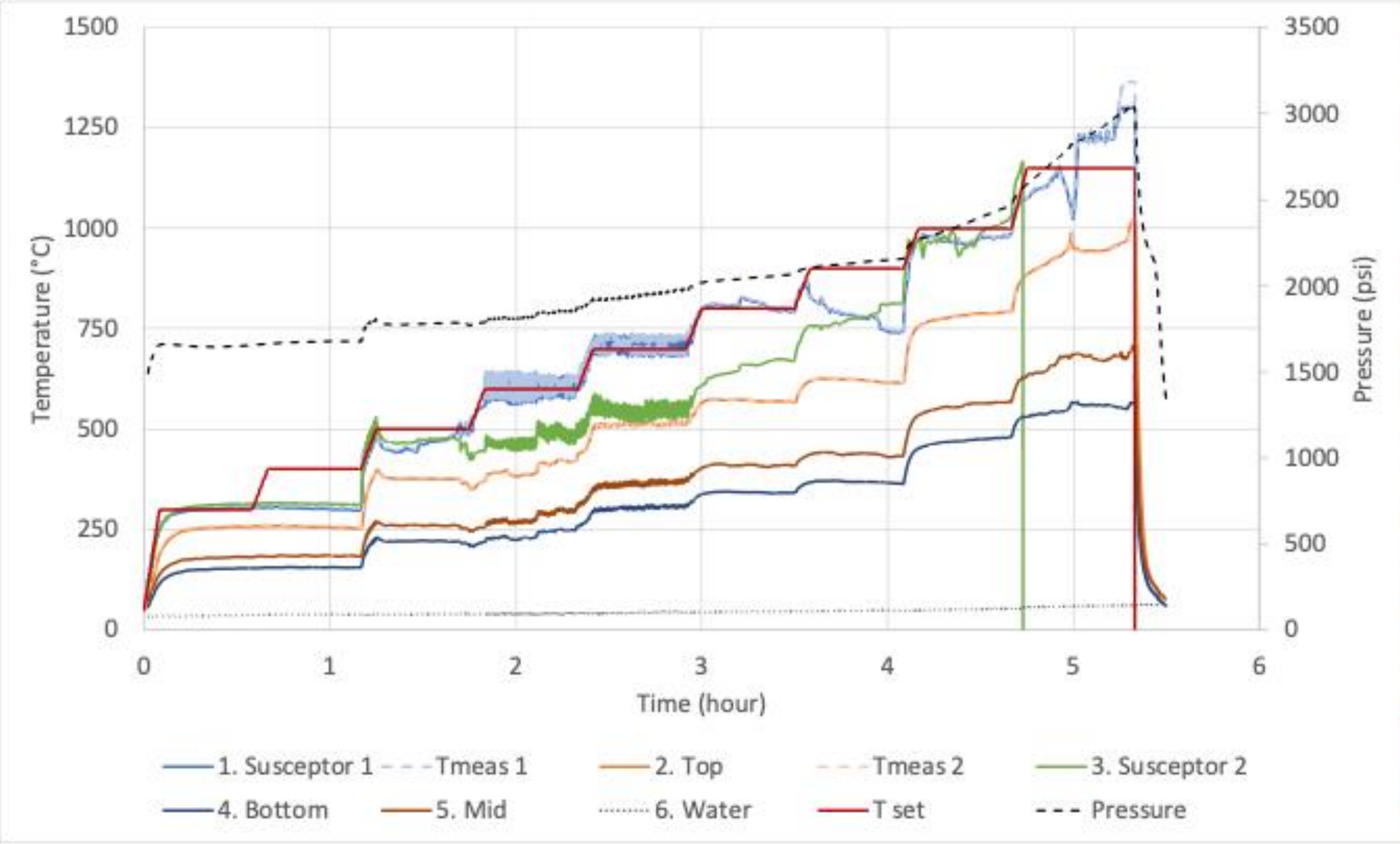
Autoclave material testing

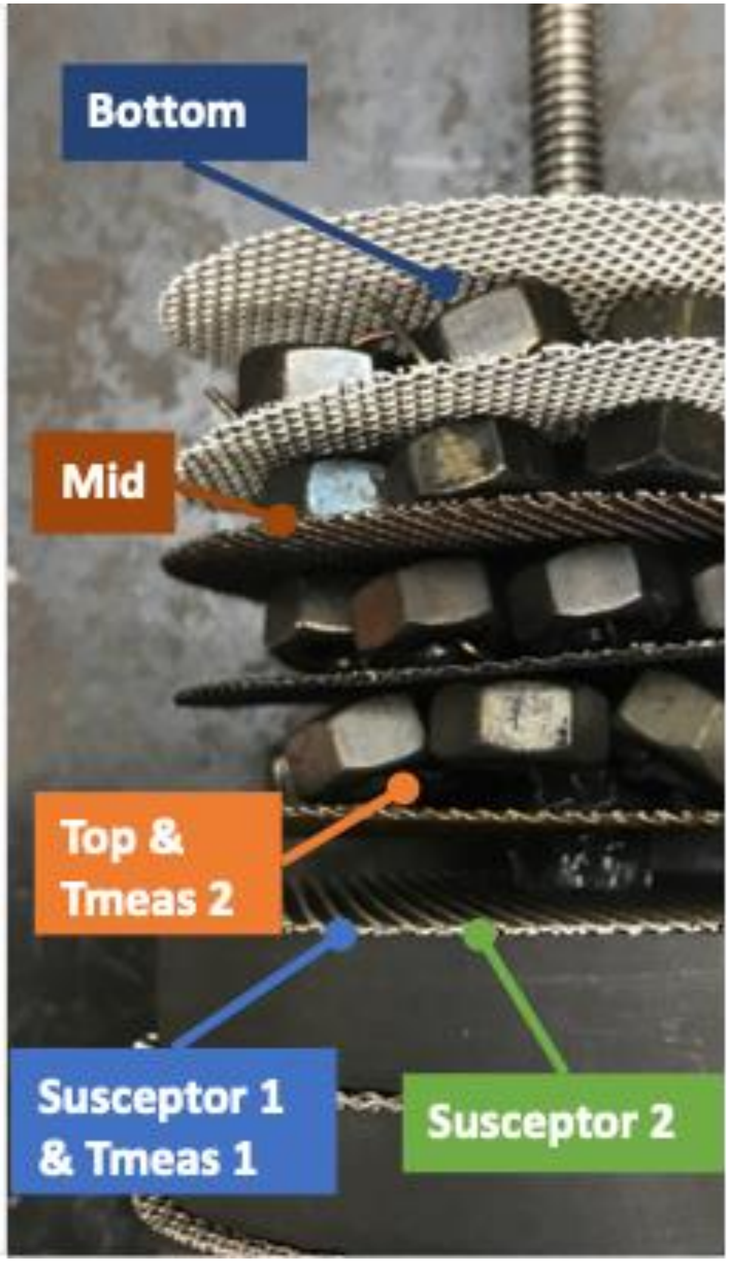




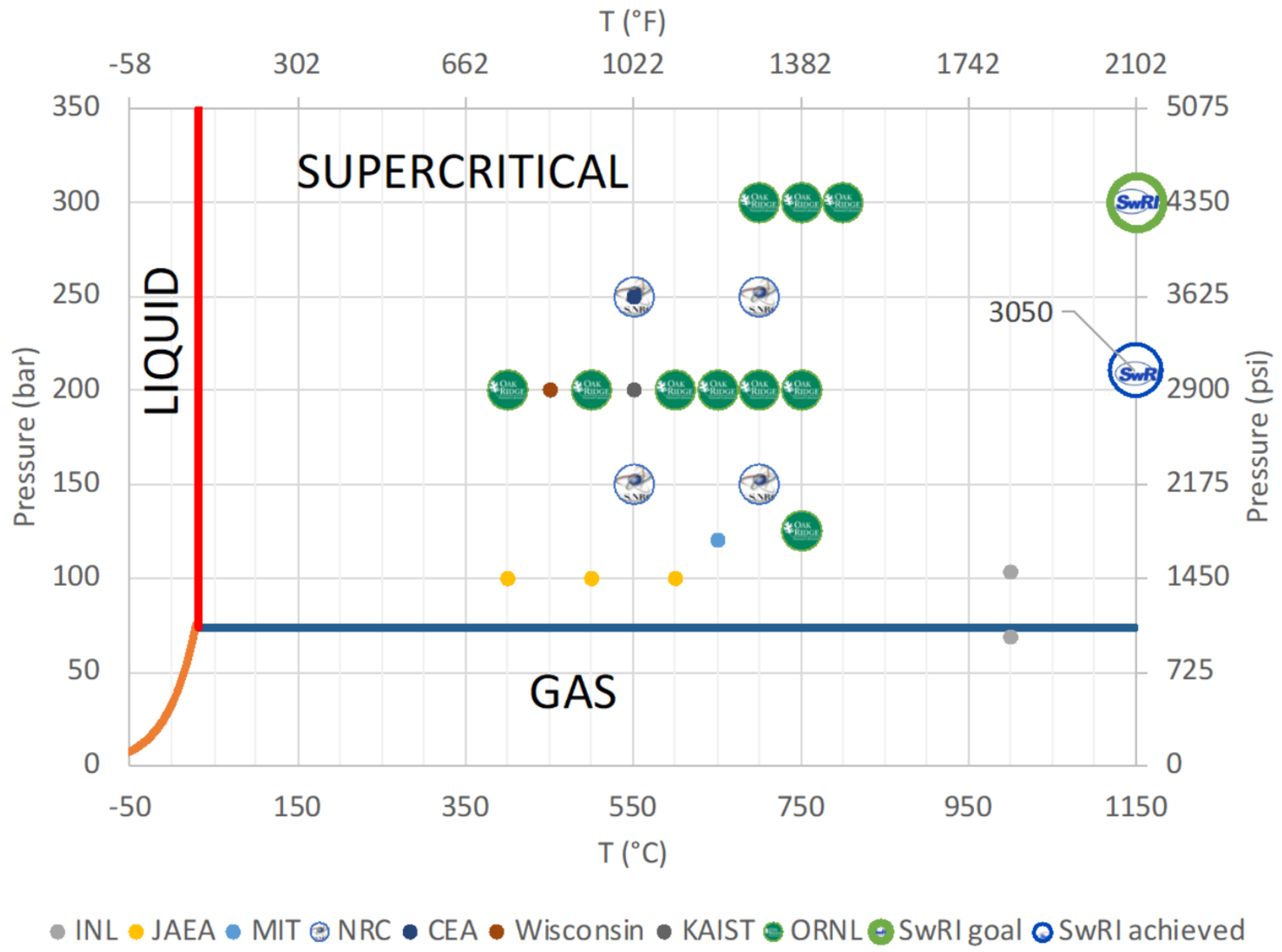
- Autoclave tests are for turbine materials and coatings exposure to observe oxidation characteristics at turbine inlet conditions.
- An induction heater with susceptor is used with TCs inserted to measure temperature throughout stack of material samples.

Autoclave material testing



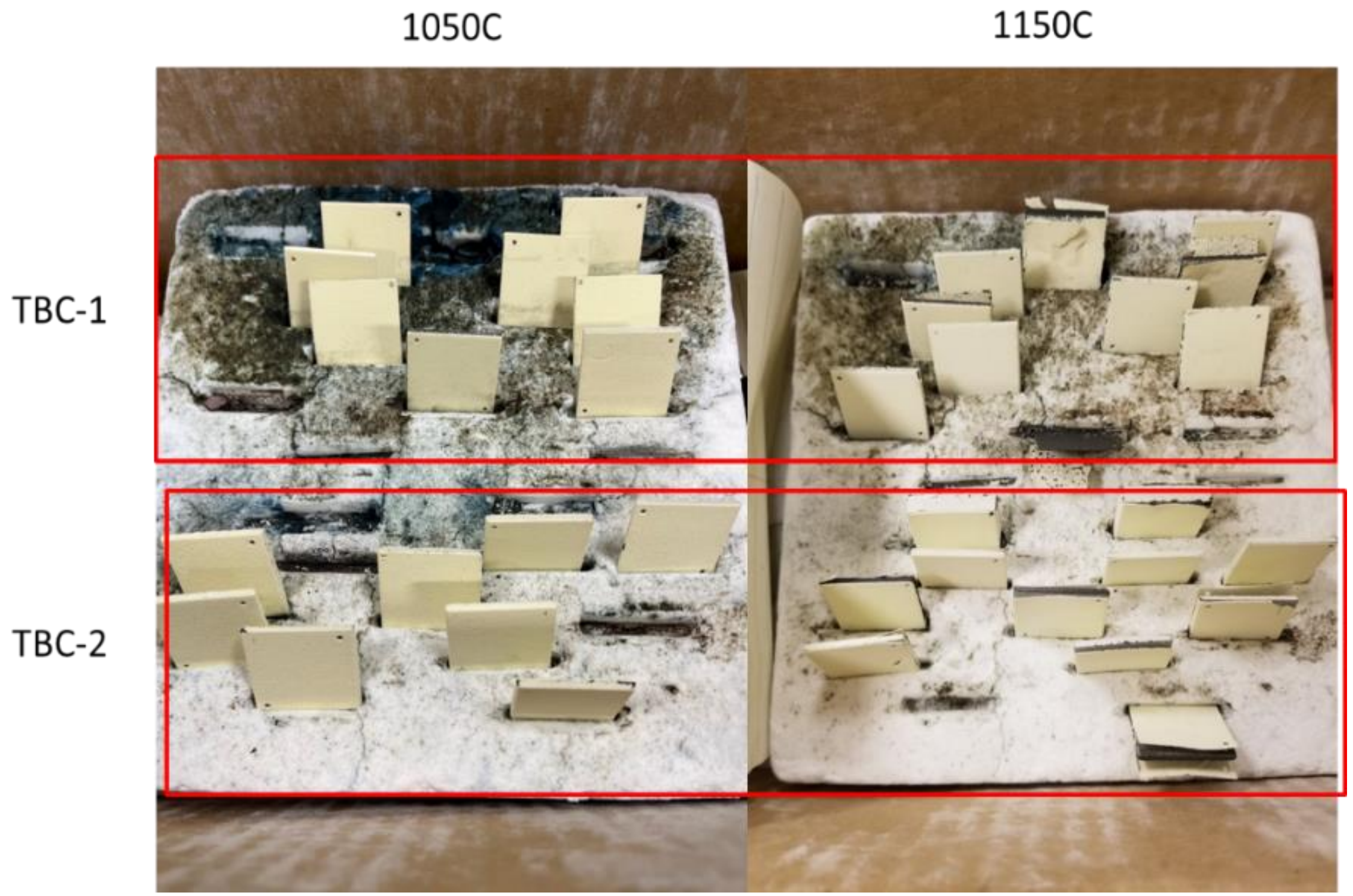


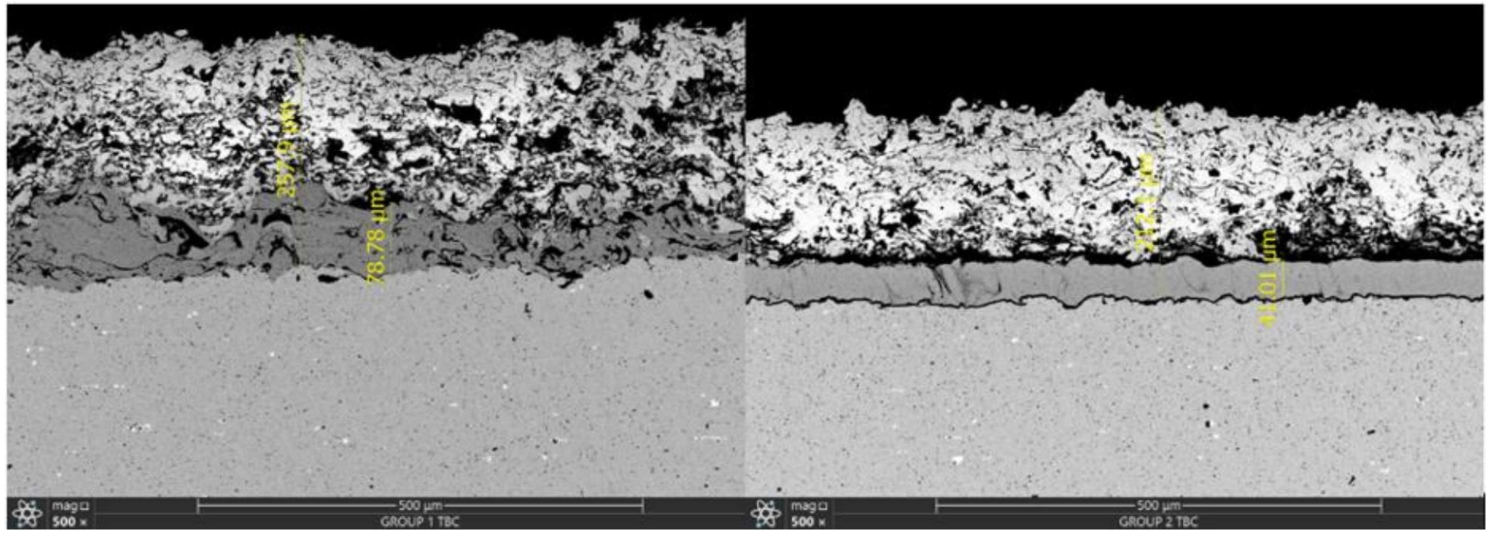
Autoclave material testing



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

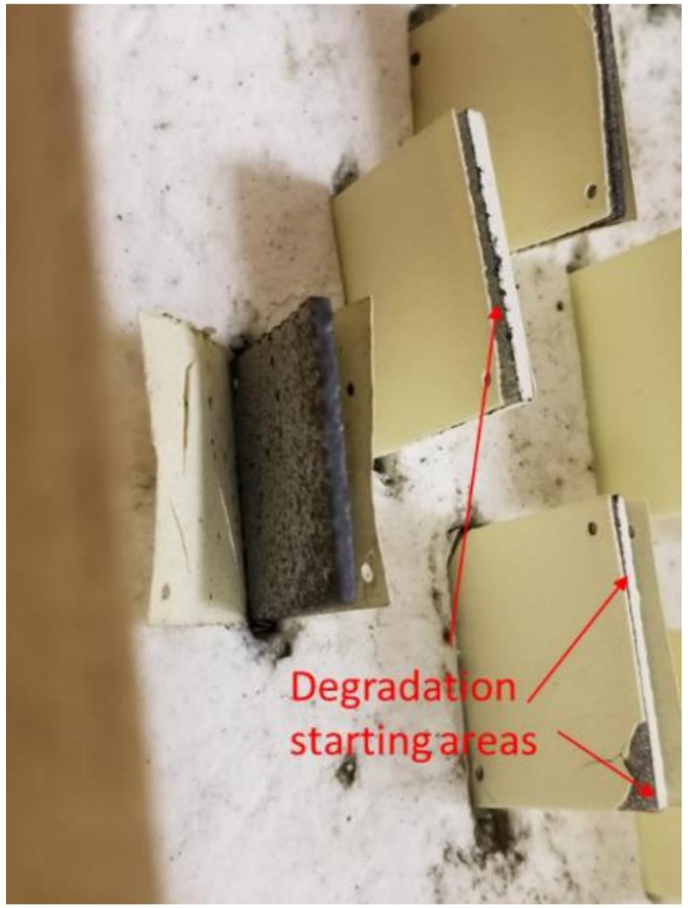
TBC Cyclic Testing

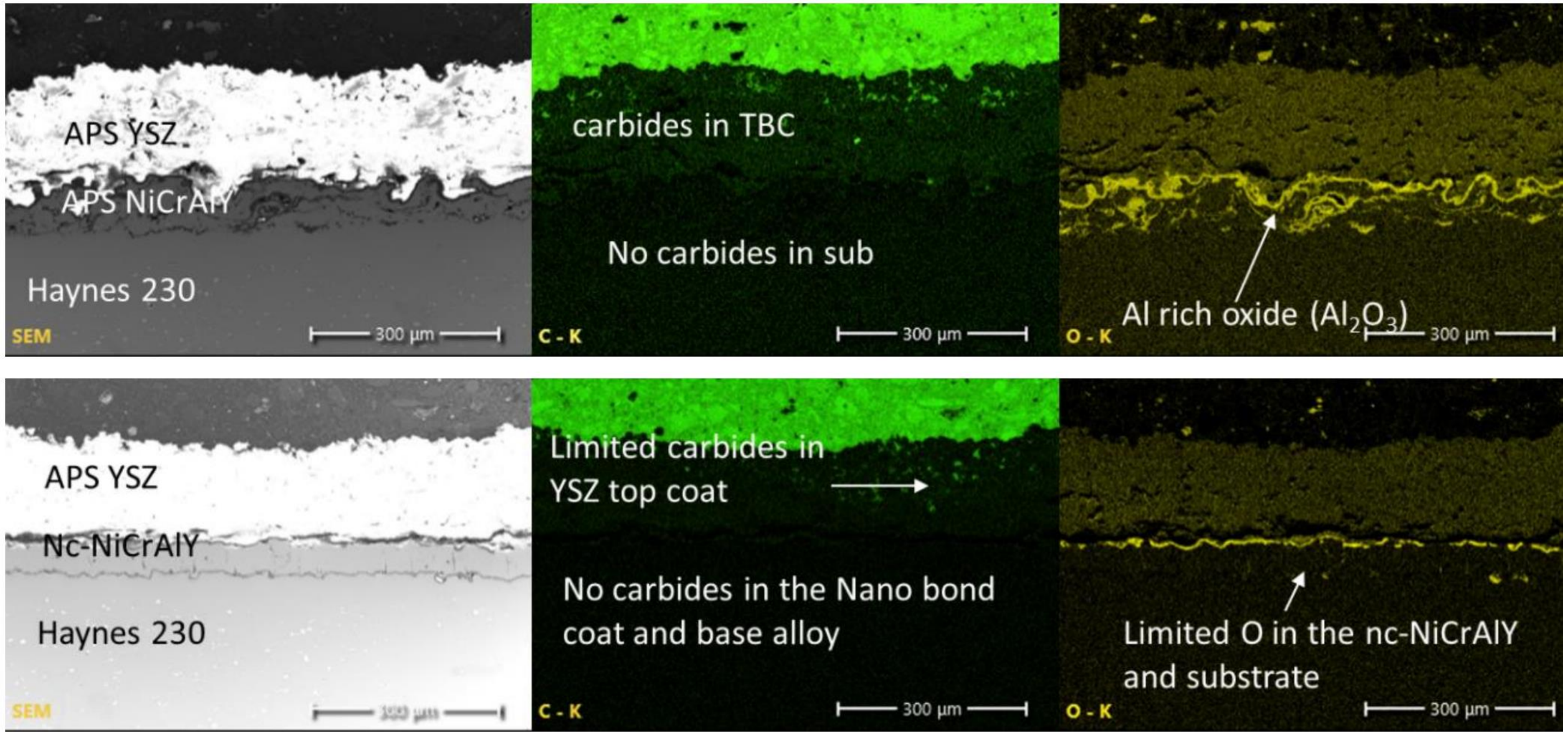




- 500 cycles
  - 50 min at (1050°C or 1150°C), ambient pressure.
  - 10 min. forced air cooling.
- Two different coating methods on nickel alloy (Haynes 230 shown):
  - *Thermal spray* MCrAlY bond coat, *thermal spray* yttrium stabilized zirconia (YSZ) top coat.
  - *Plasma Enhanced Magnetron Sputtering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

TBC cyclic testing



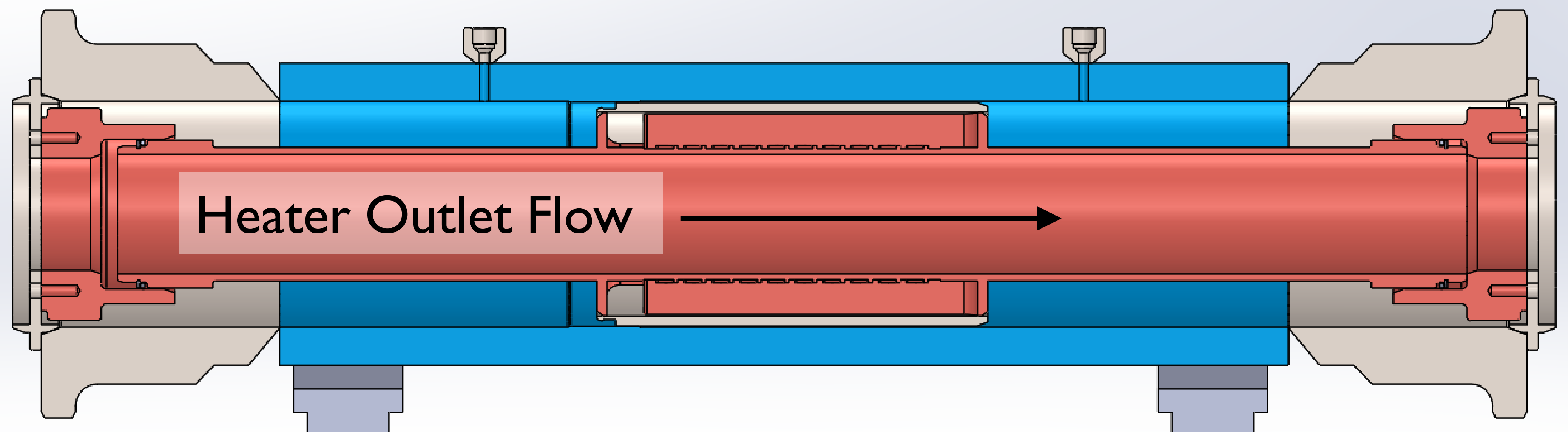


- Degradation seen on almost all samples for 1150°C cycling.
- PEMS bond coat witnessed significantly less carbide and oxide attack than thermal sprayed bond coat.

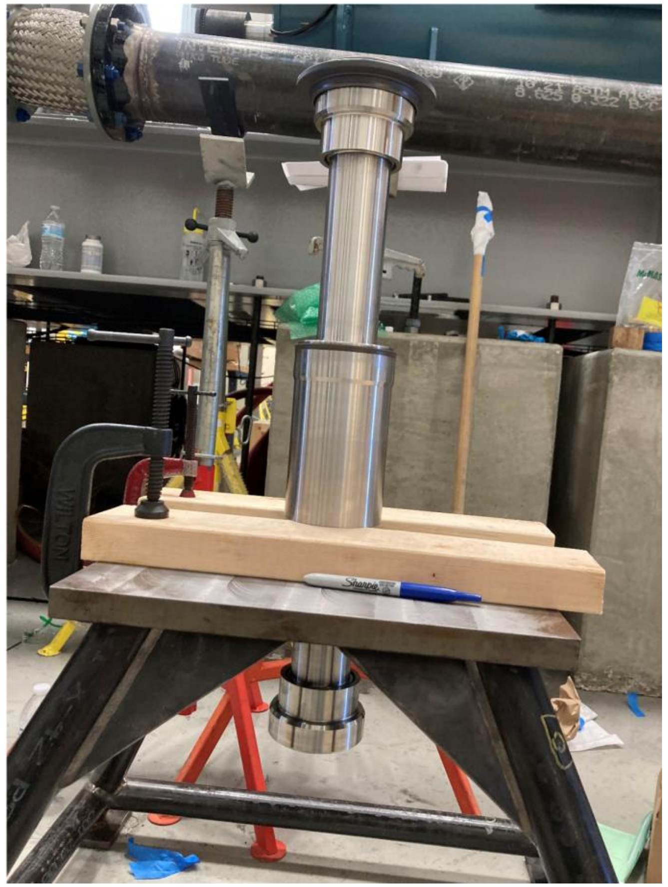
Component Testing

High RE heat transfer testing

- A plethora of midsection ribbed cooling is available up to a RE number of ~50,000 based on air-breathing engine.
- What happens with sCO_2 at internal cooling RE numbers 100k – 400k?

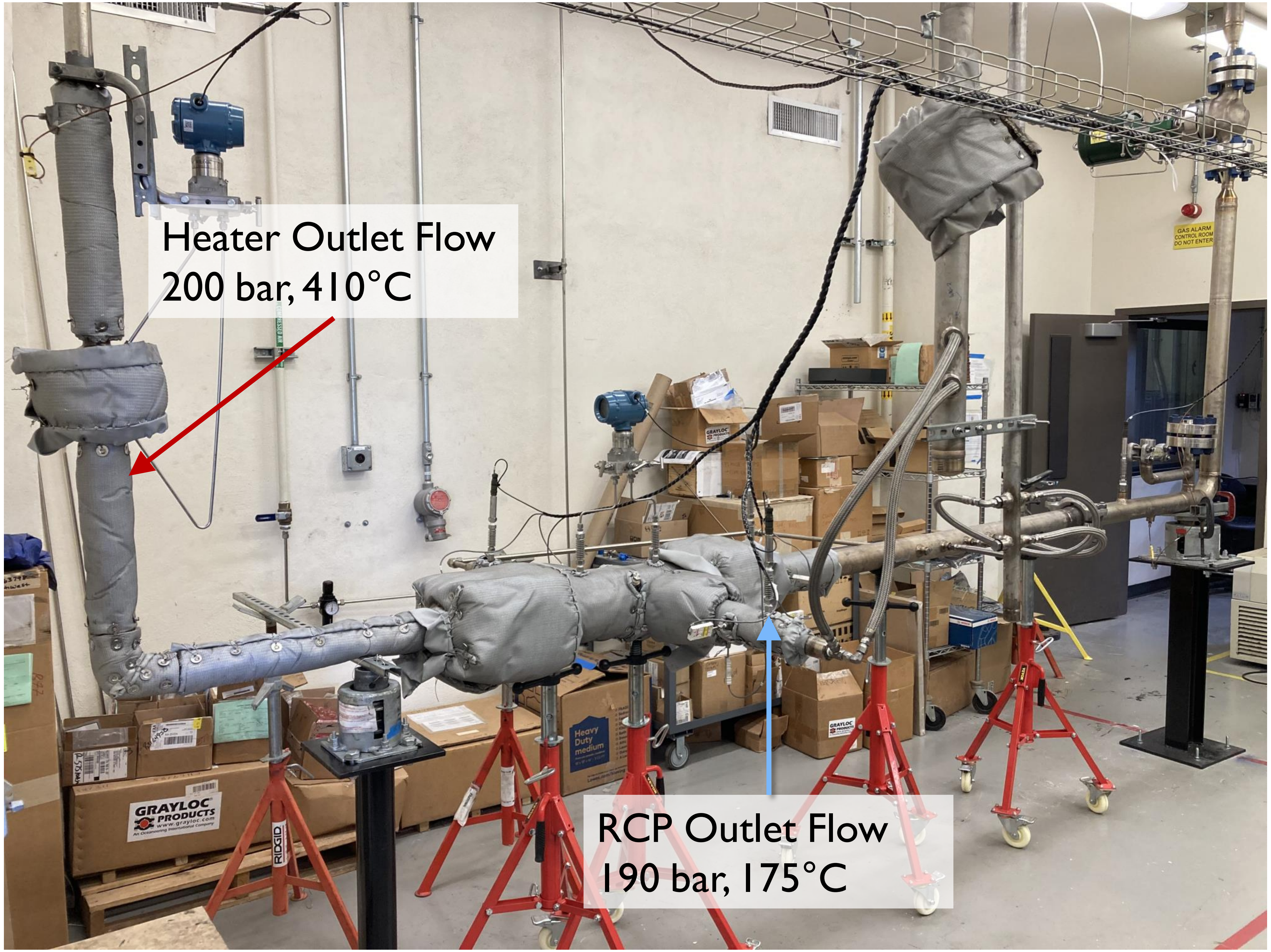


High RE heat transfer testing

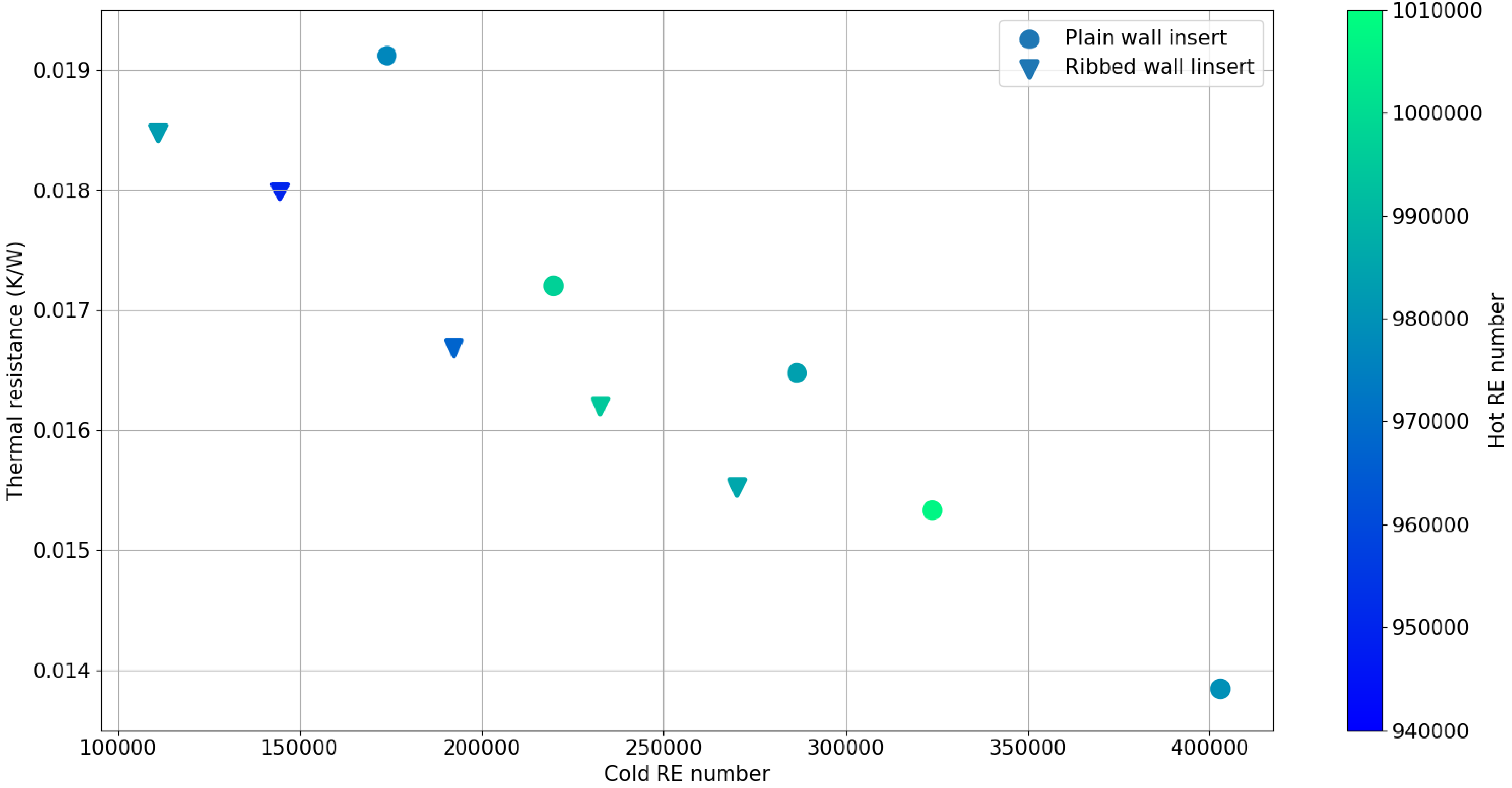



- Assembly and disassembly between interchangeable inserts can be completed in 5 hrs.

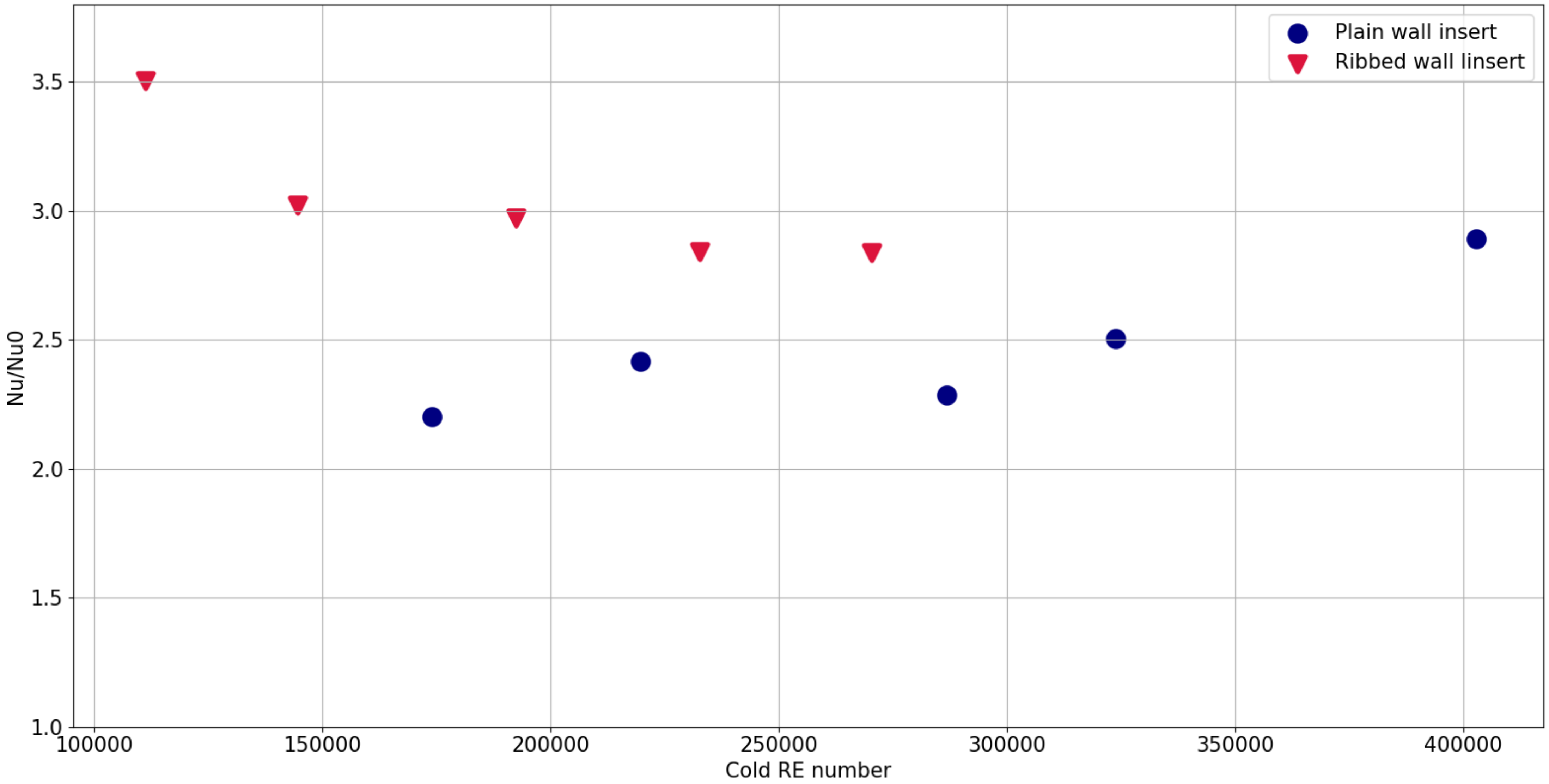
High RE heat transfer testing



High RE heat transfer testing



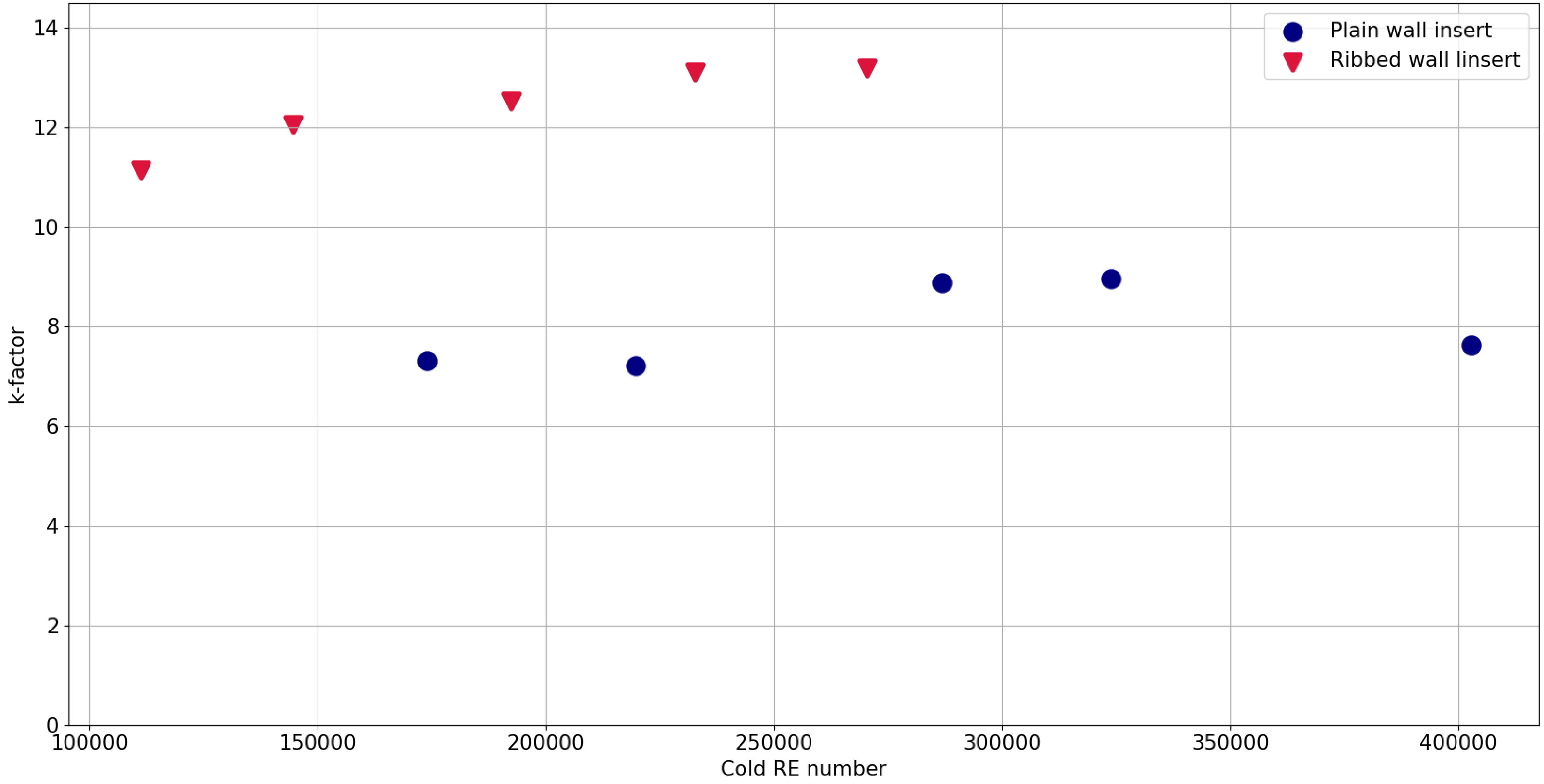
High RE heat transfer testing



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.

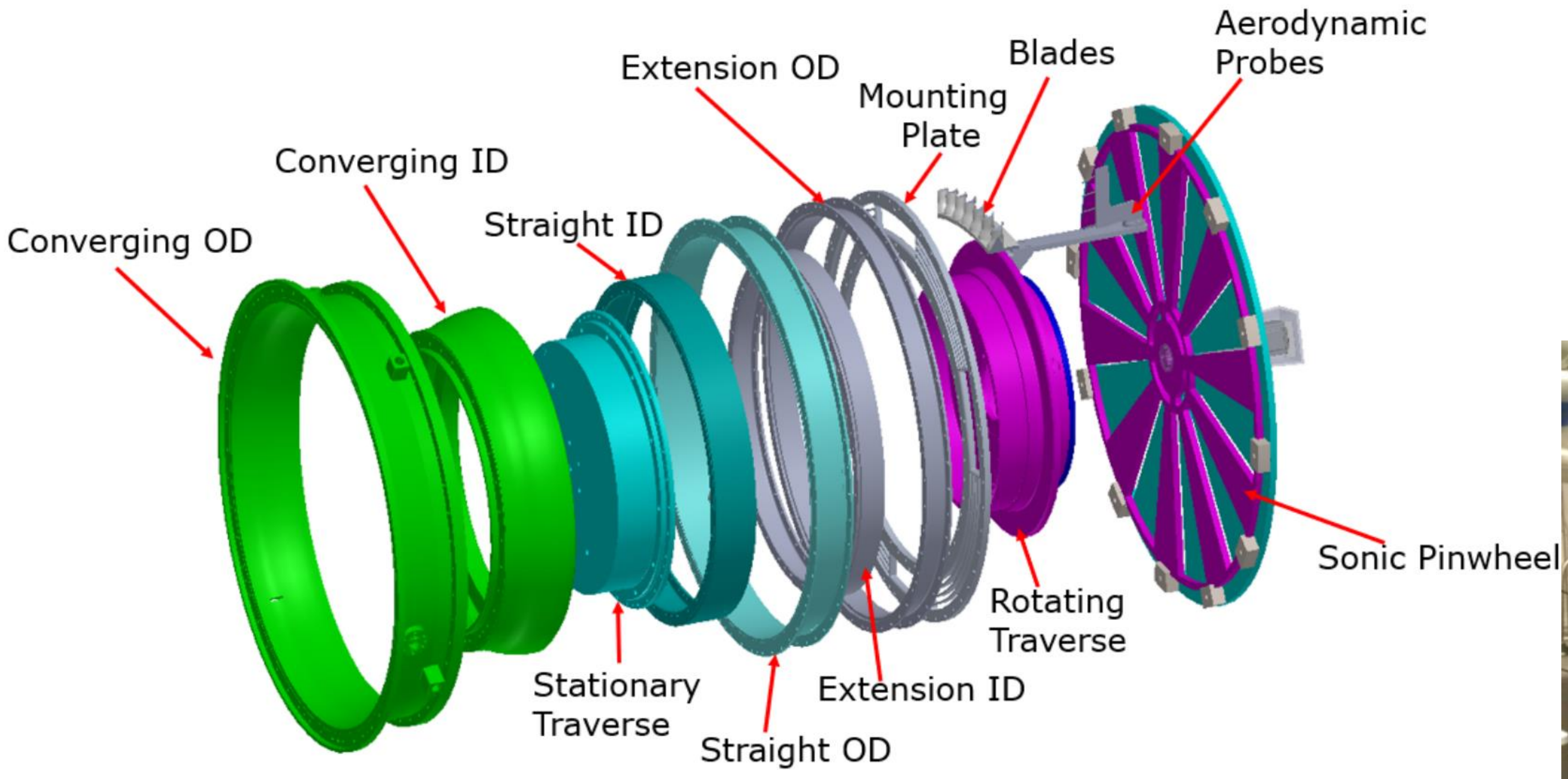
High RE heat transfer testing

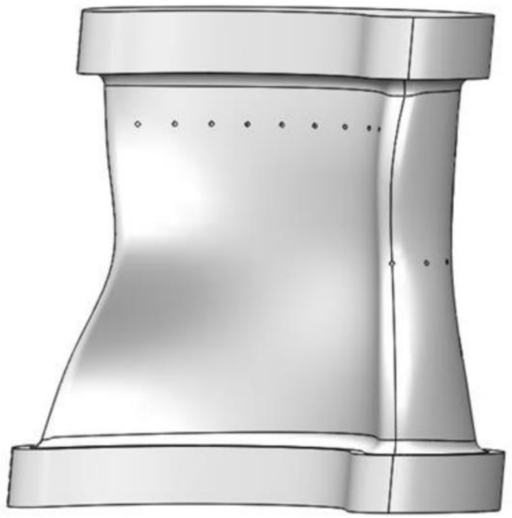
$$k = \frac{\Delta P}{\frac{\left(\frac{\dot{m}_{cool}}{2A_{pass}}\right)^2}{2\rho}}$$

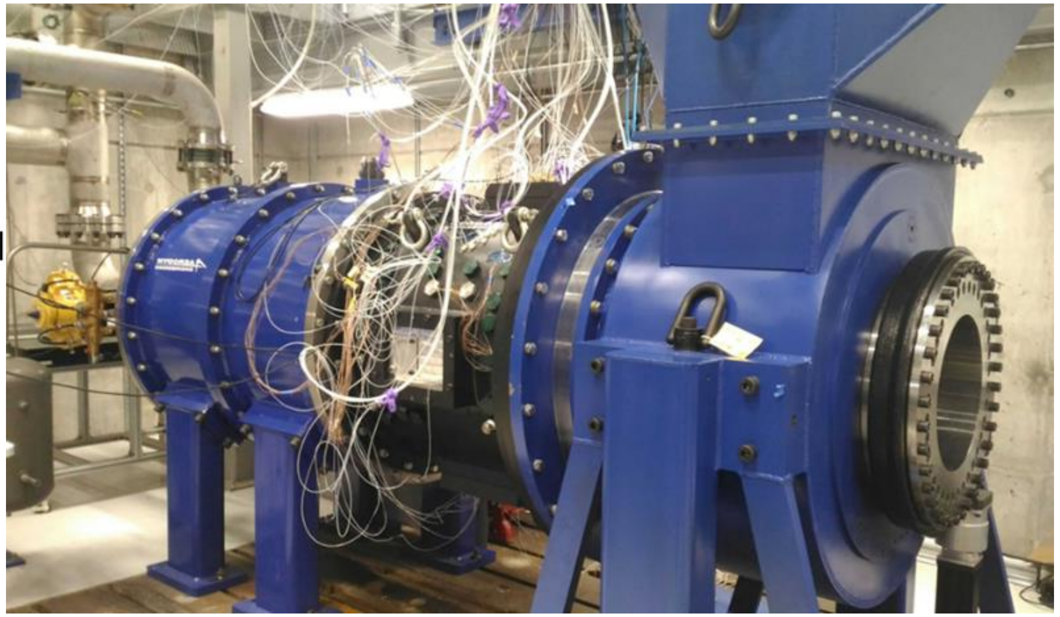


A dP transmitter measures the pressure loss across the serpentine passage with five passes.

S1B cascade testing

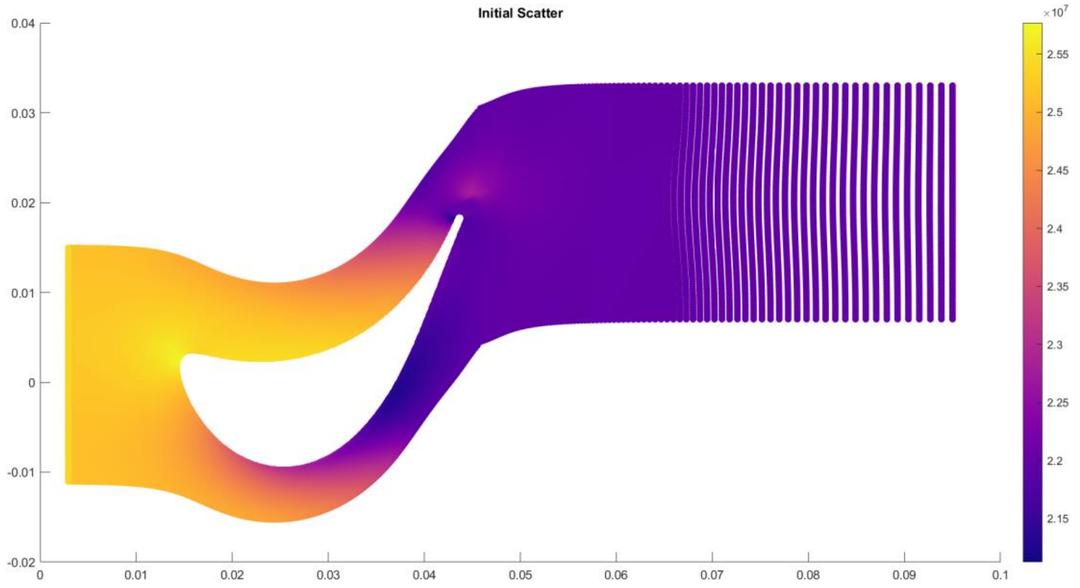


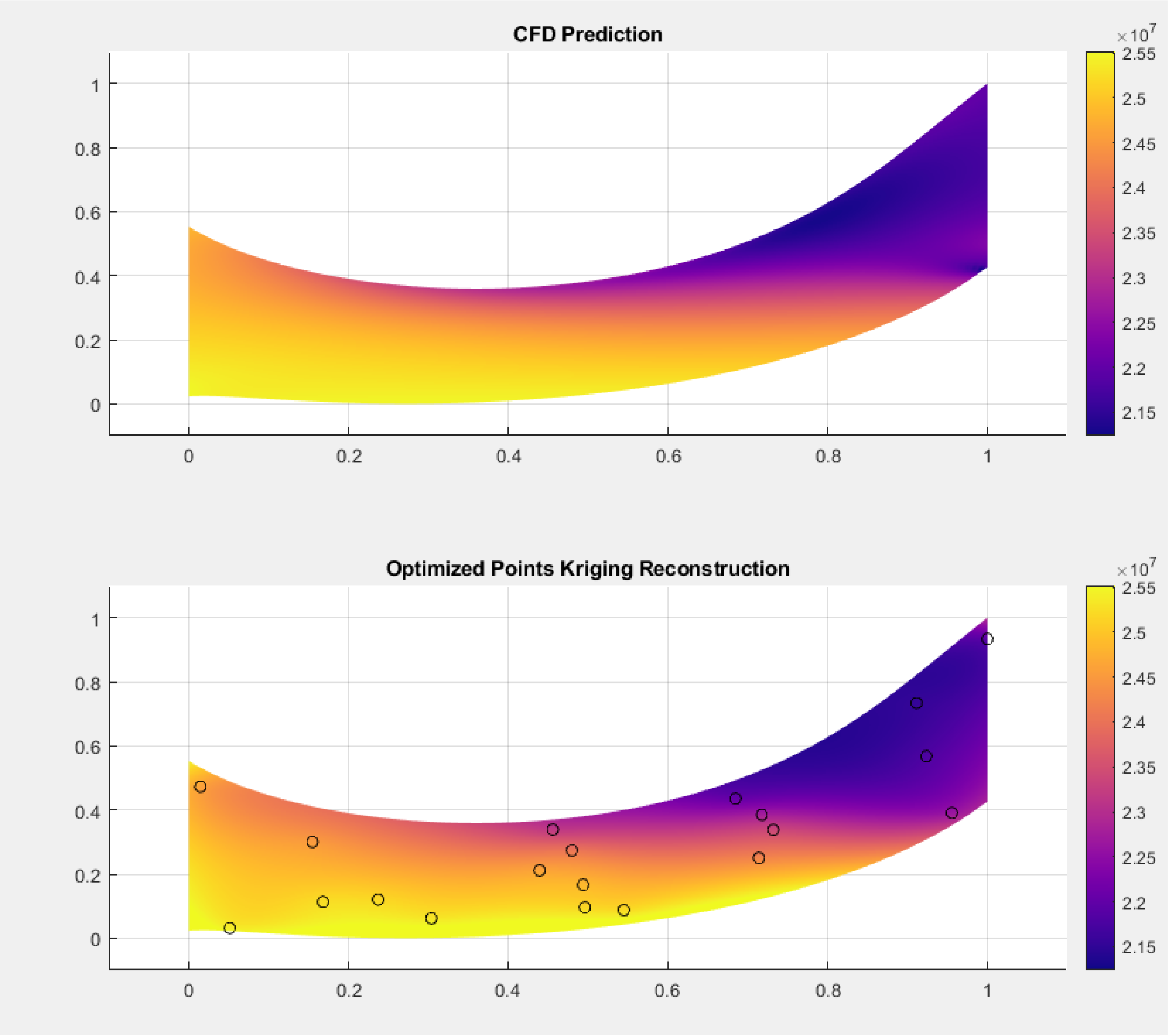




- Commissioning is underway at the Purdue Big Rig for Aerothermal Stationary Turbine Analysis (BRASTA) for a S1B cascade test.

S1B cascade testing

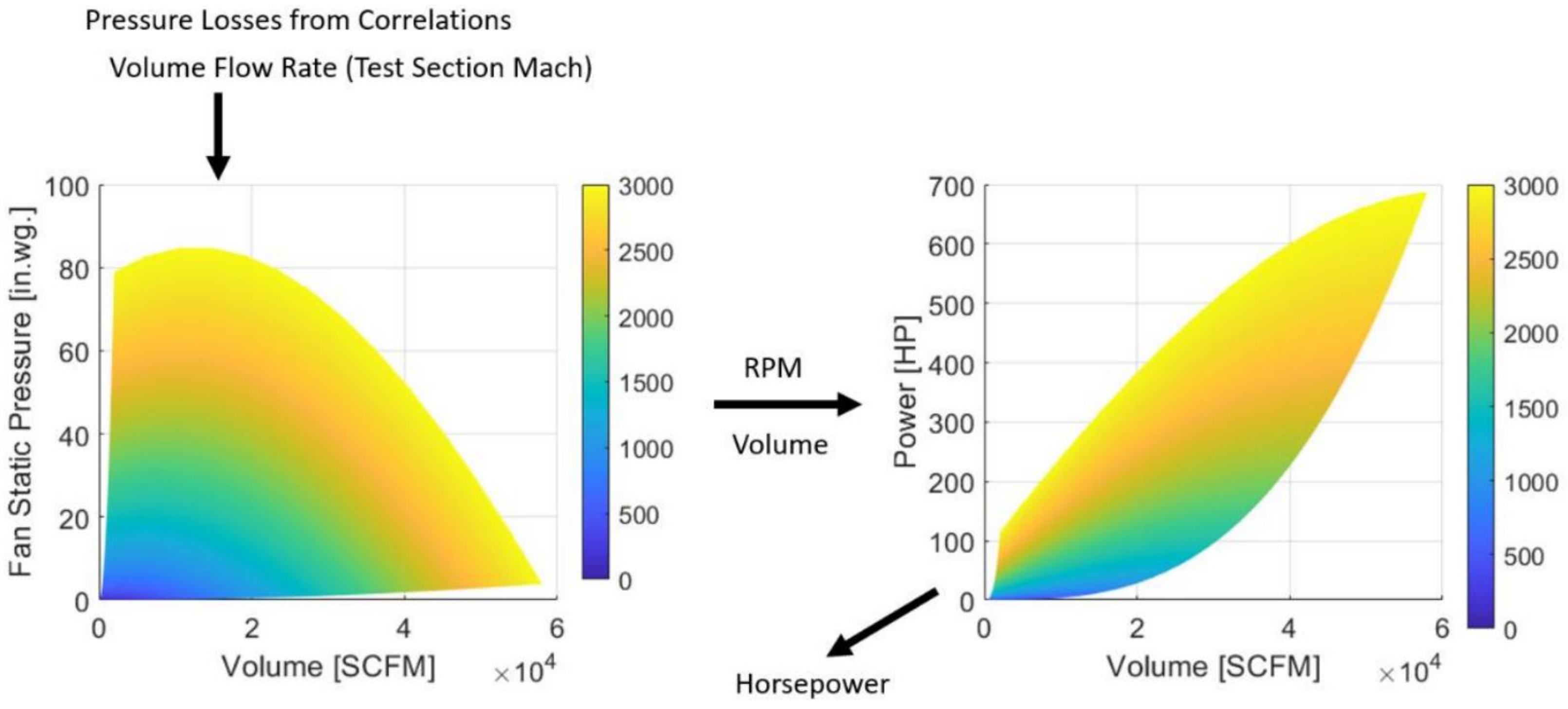


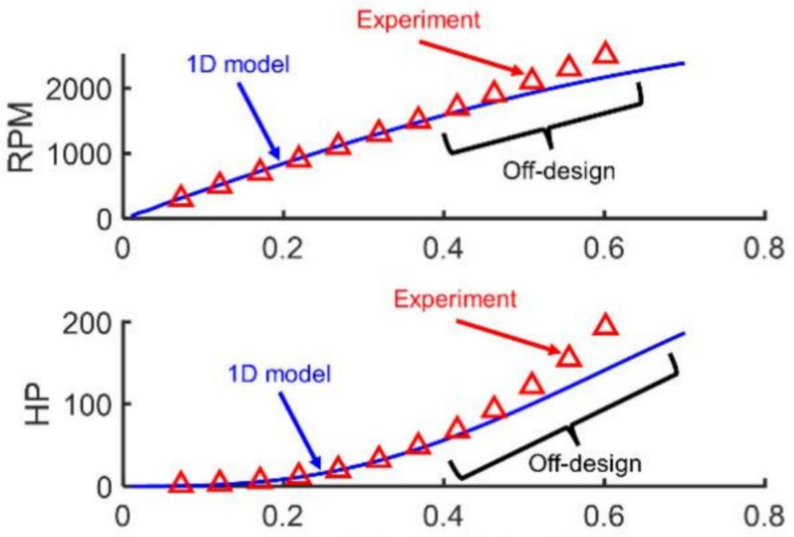


- Optimization methods are being used based on CFD analysis to optimize pressure tap location to reconstruct blade loading.

S1N-S1B cavity testing

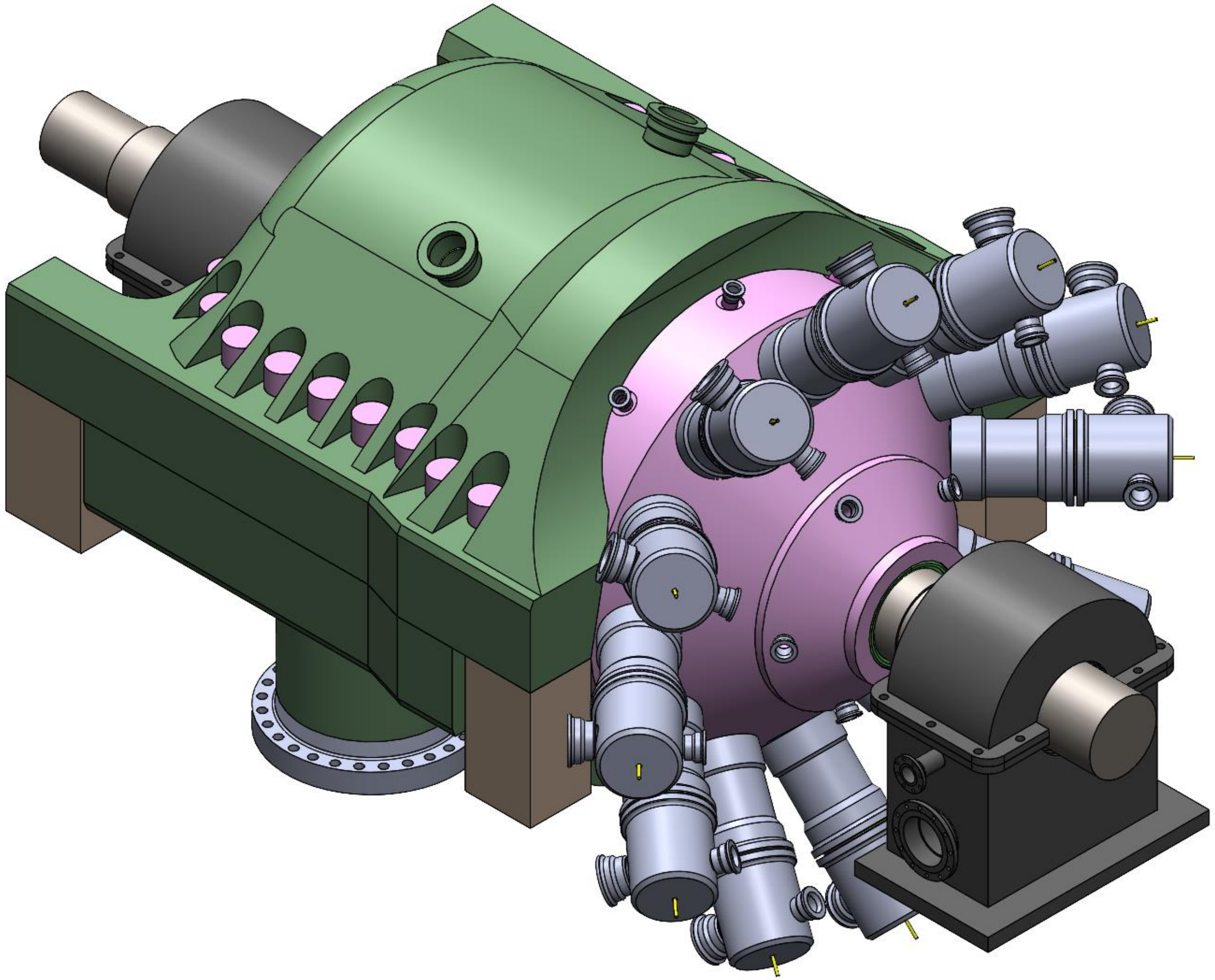
- Commissioning of subsonic wind tunnel is taking place to capture operating range during testing of cavity upstream of S1B.

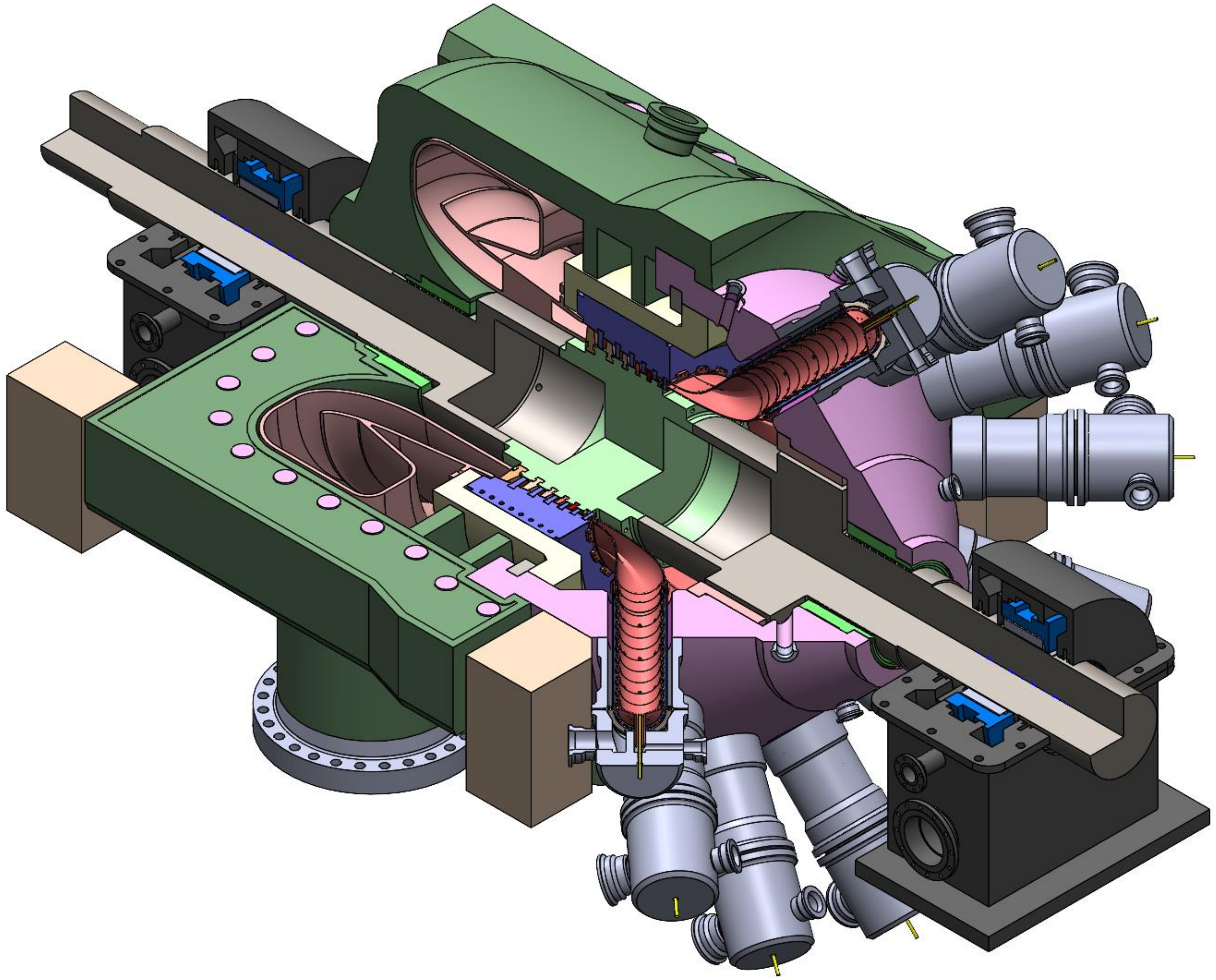




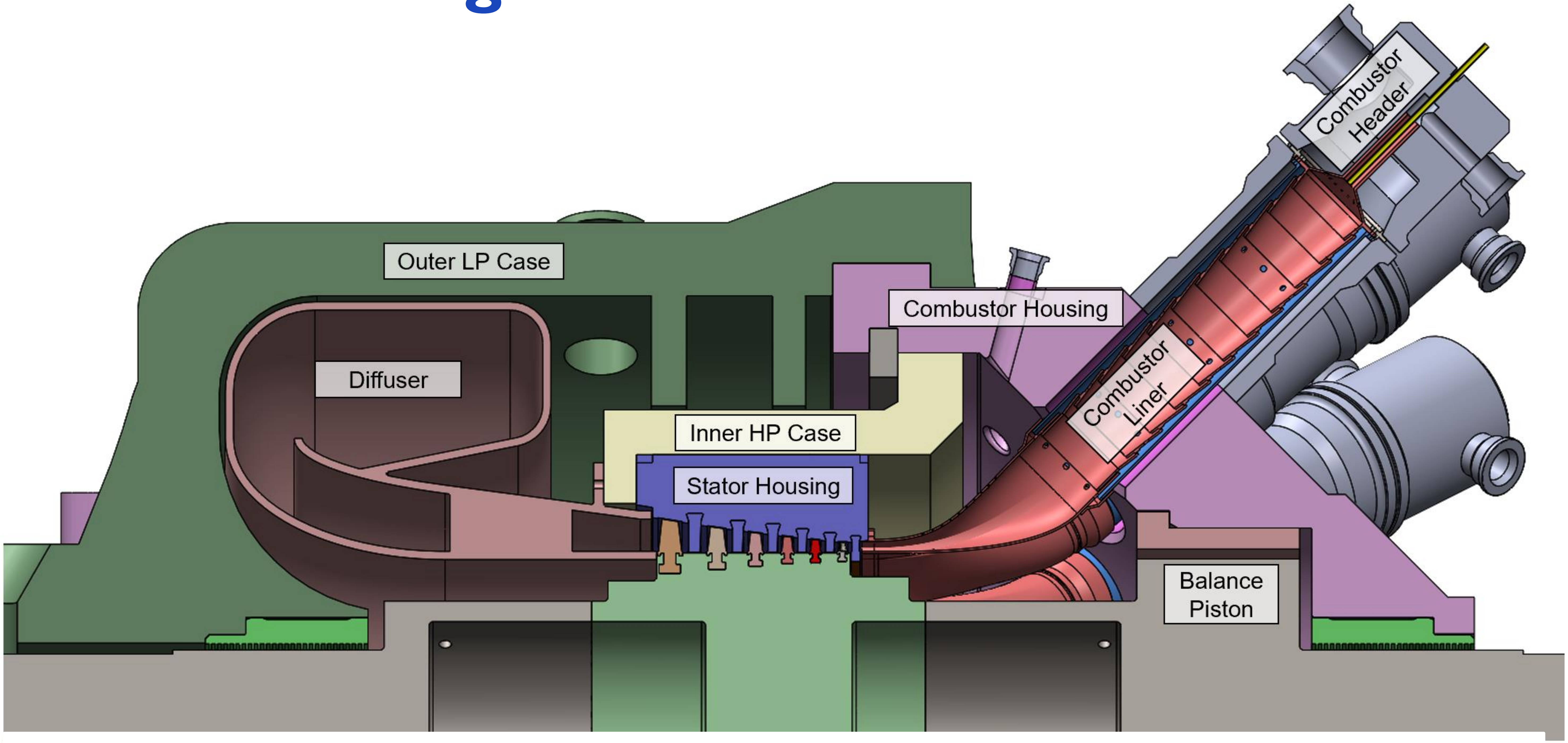
Turbine Design

Turbine design



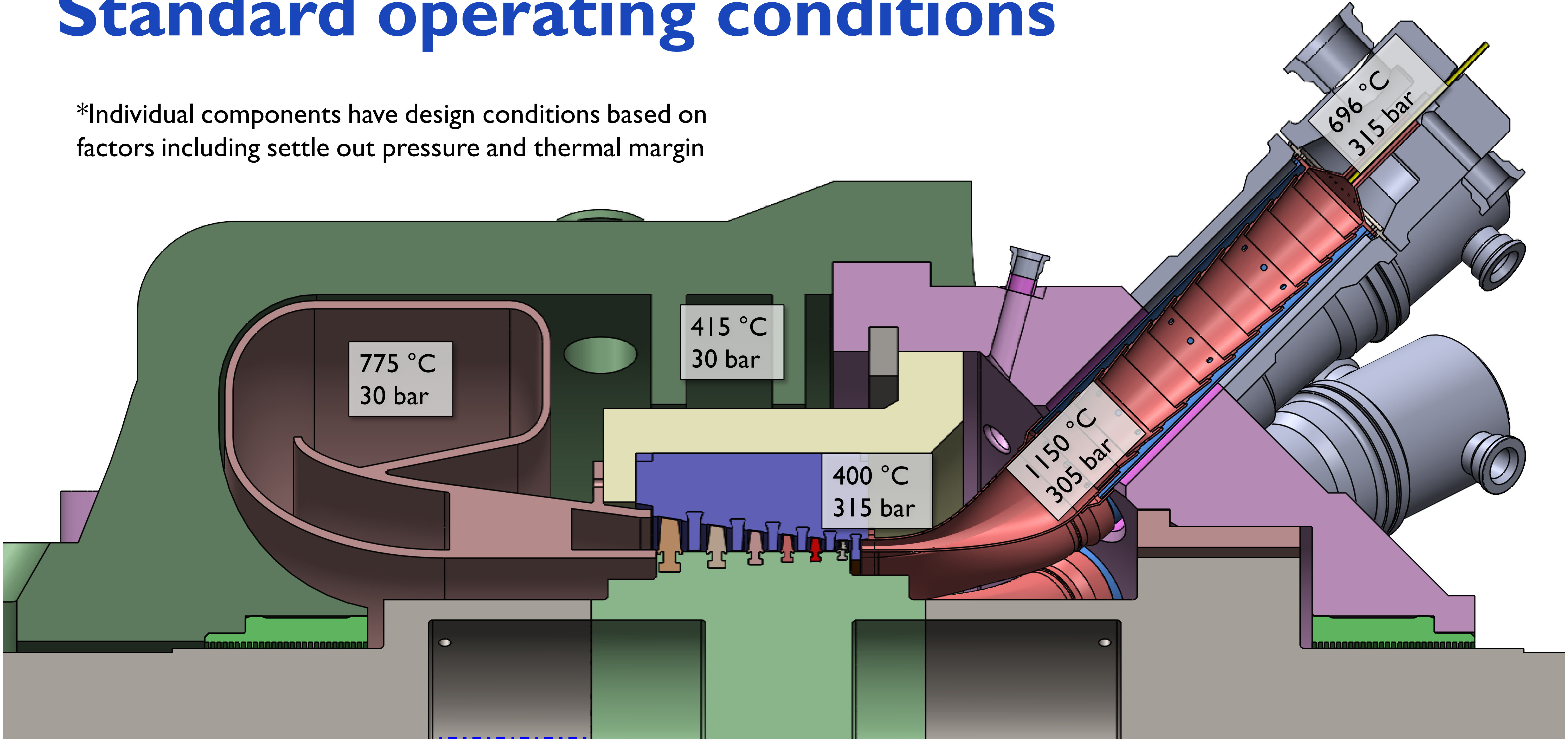


Turbine design



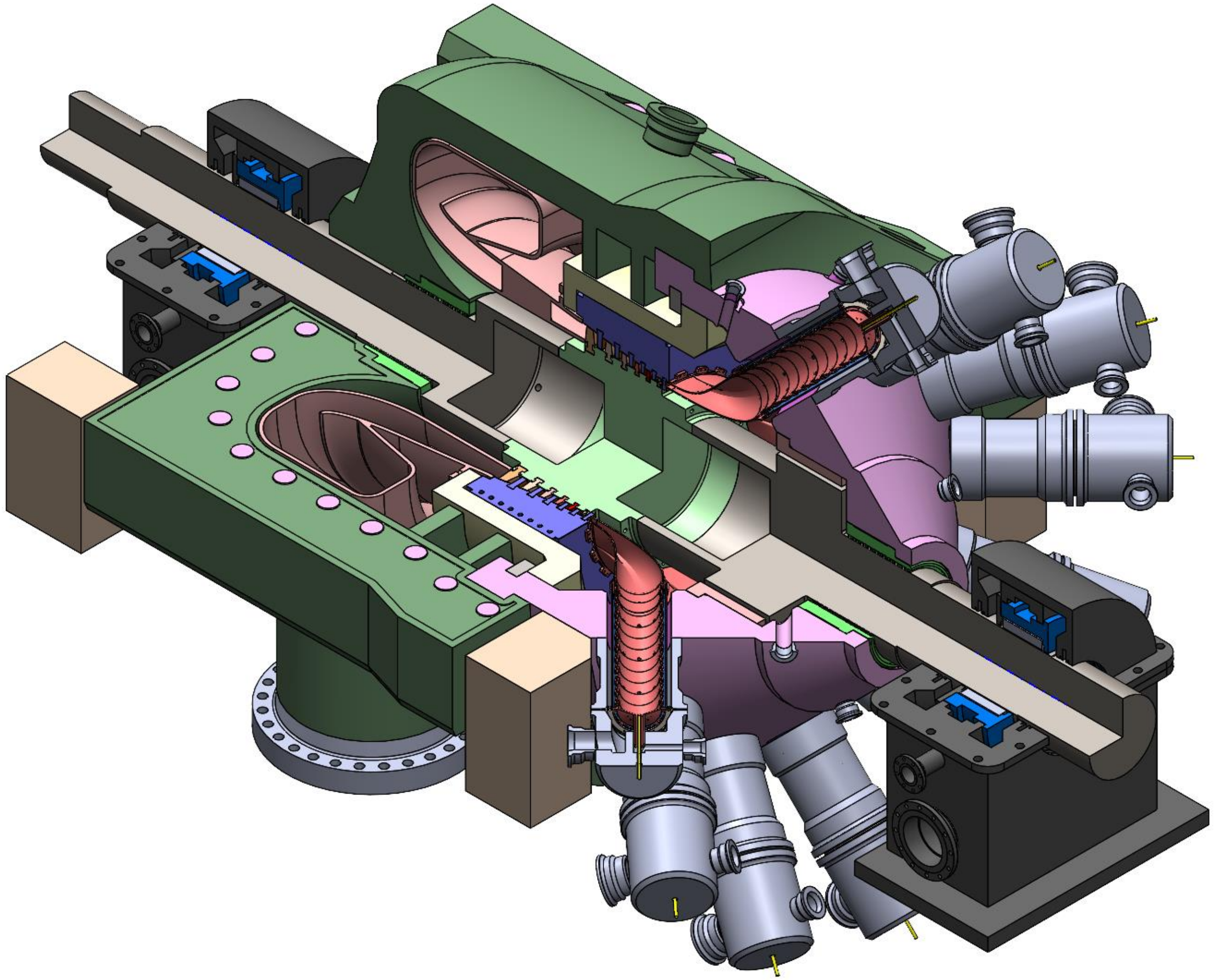
Standard operating conditions

*Individual components have design conditions based on factors including settle out pressure and thermal margin

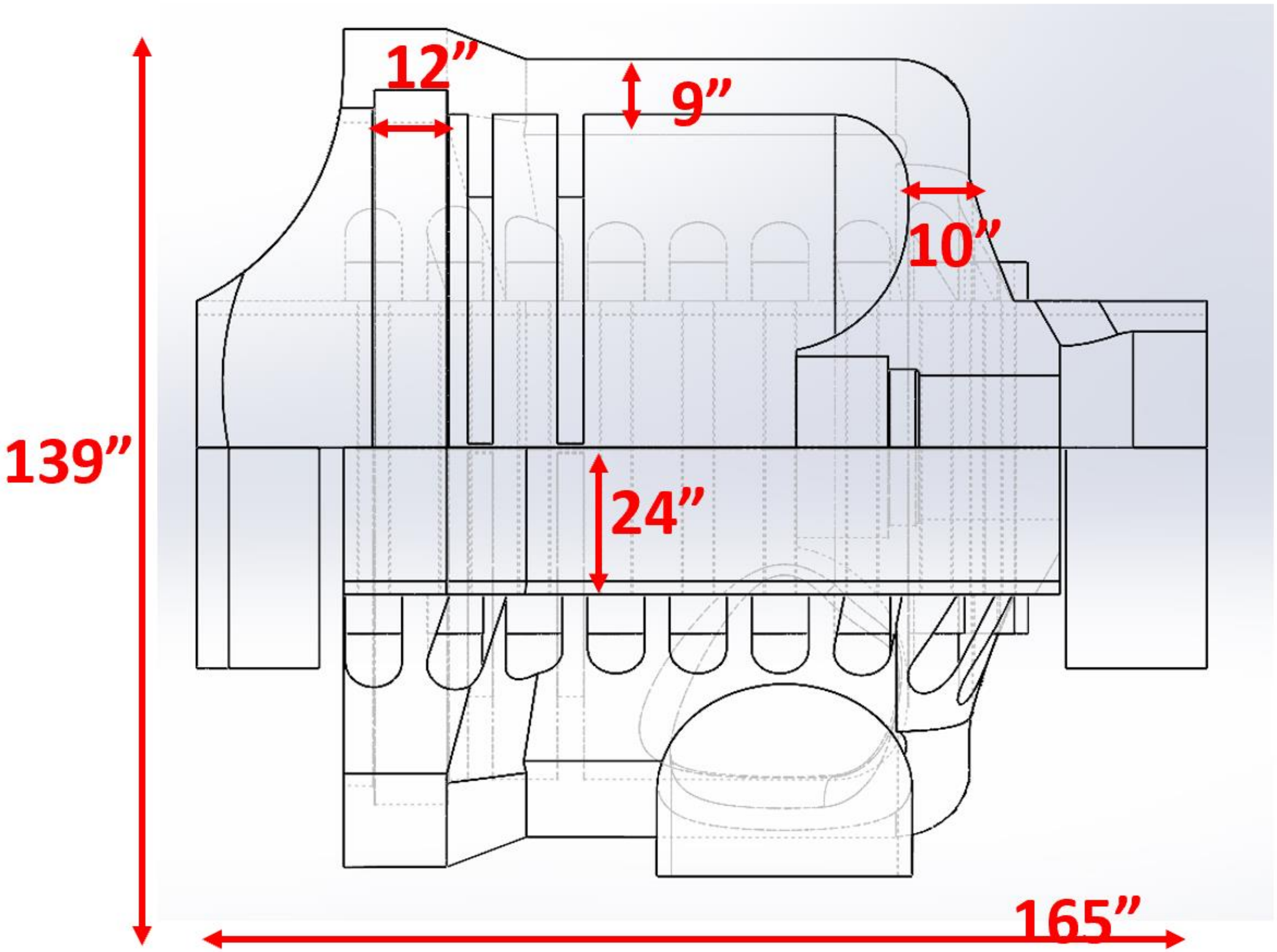


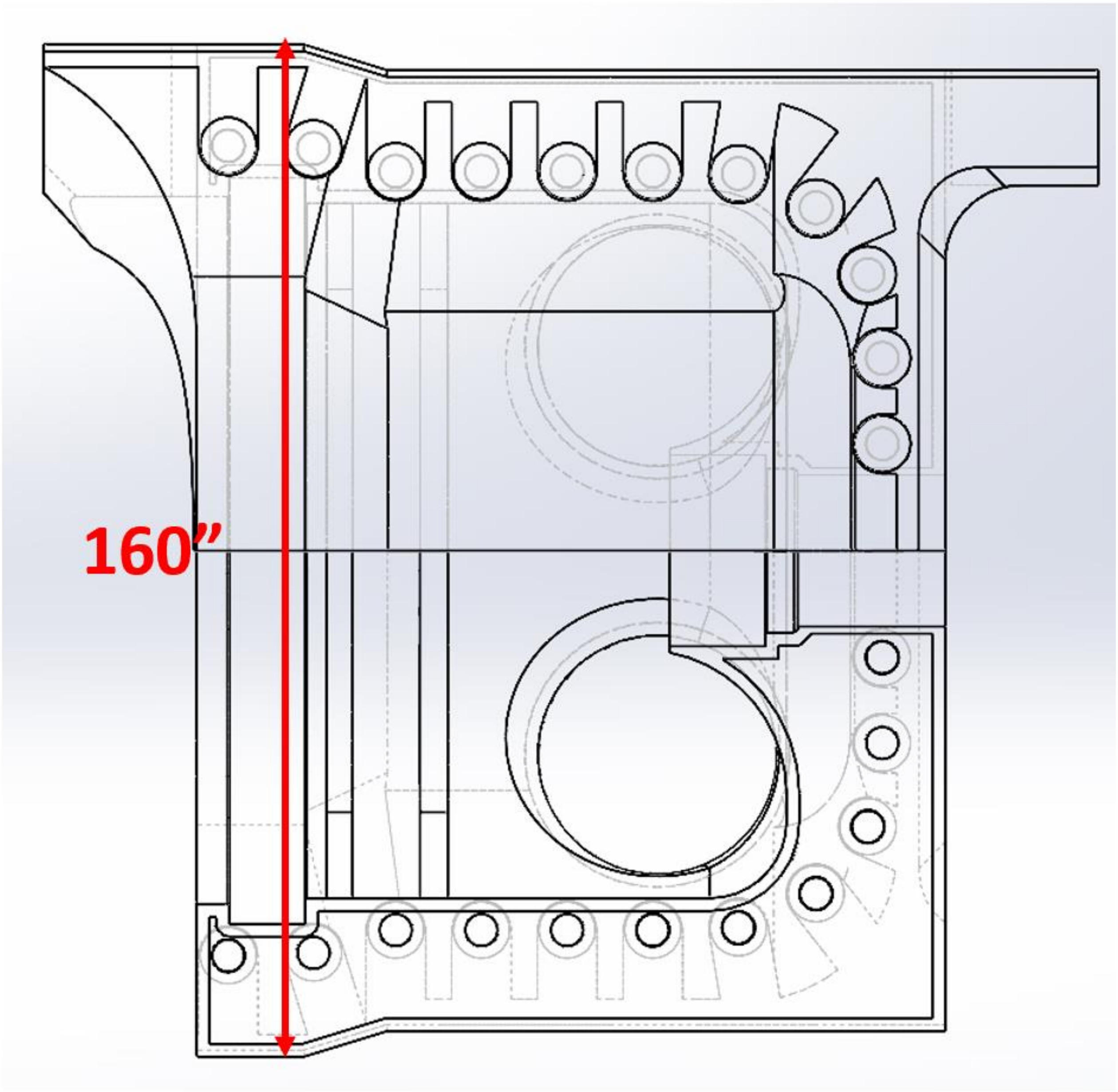
Target design criteria

- Hot section component lifetime (combustor, transition duct, S1N, S1B): **30k hrs**
- Rotor lifetime: **150k hrs**
- Pressure containing components designed to ASME BPVC, Section VIII.
- 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 *alloy steels below their creep regime.*



Outer case geometry



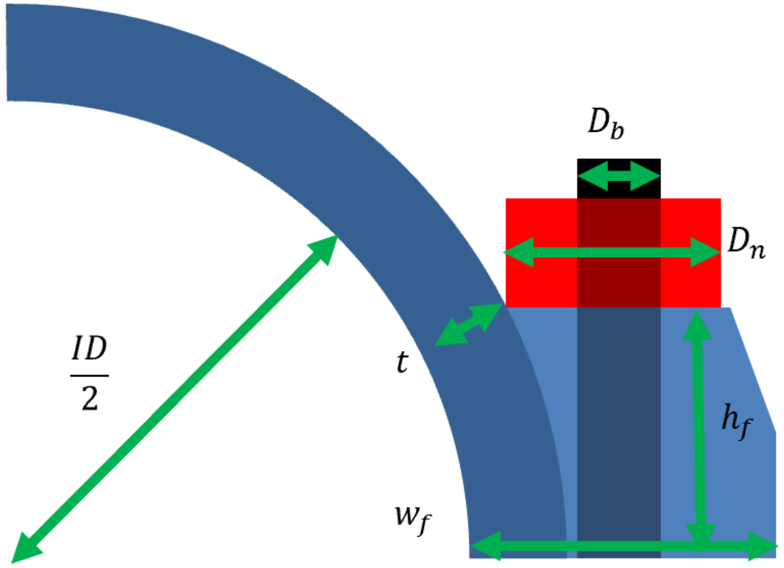


Outer case design tools

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

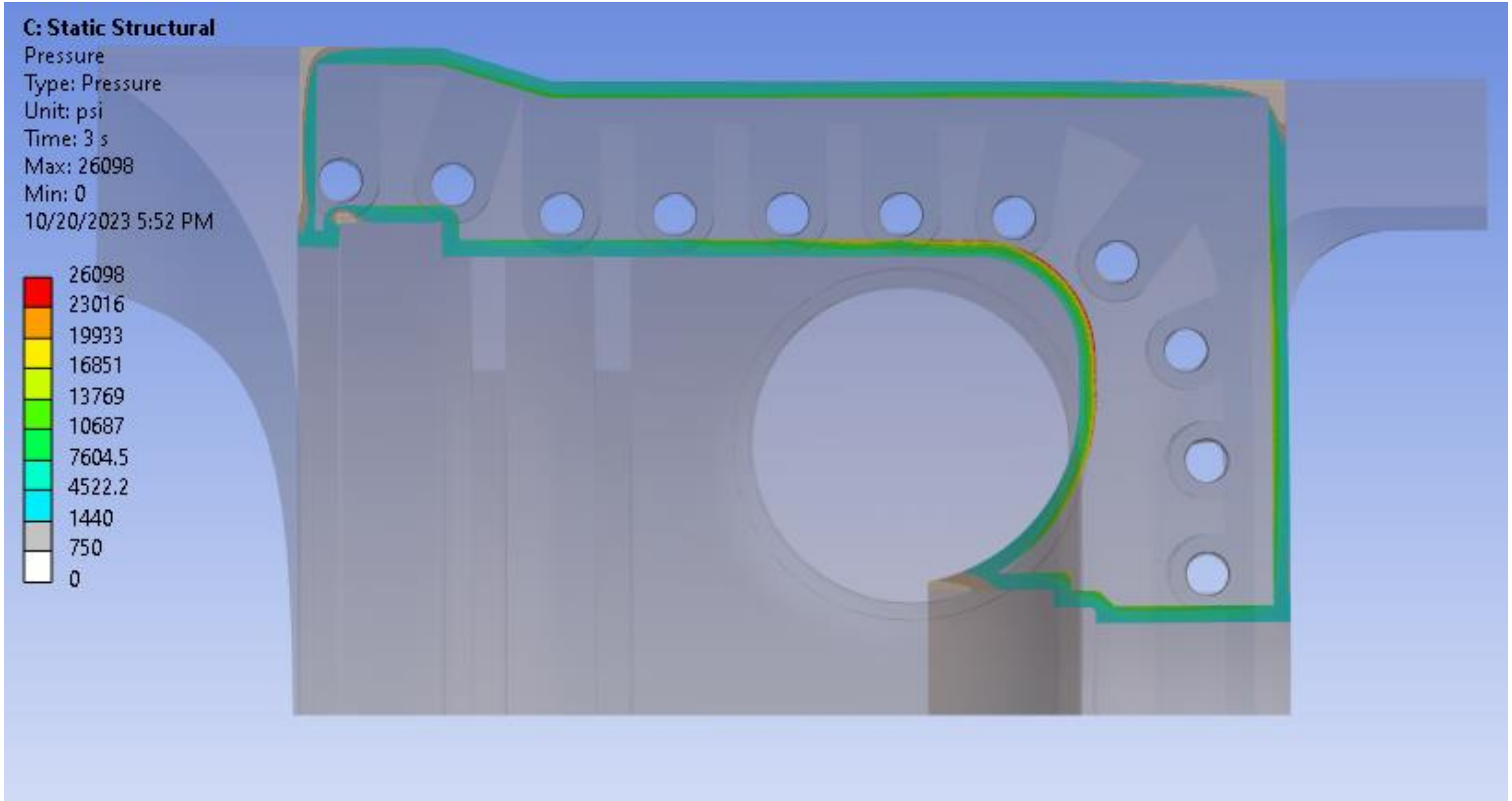
INNER CASE: Axial Load		23E+6	lbf
COMBUSTOR CASE: Axial Load		25.4E+6	lbf
OUTER CASE: Flange Separation Load		6.15E+6	lbf

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	



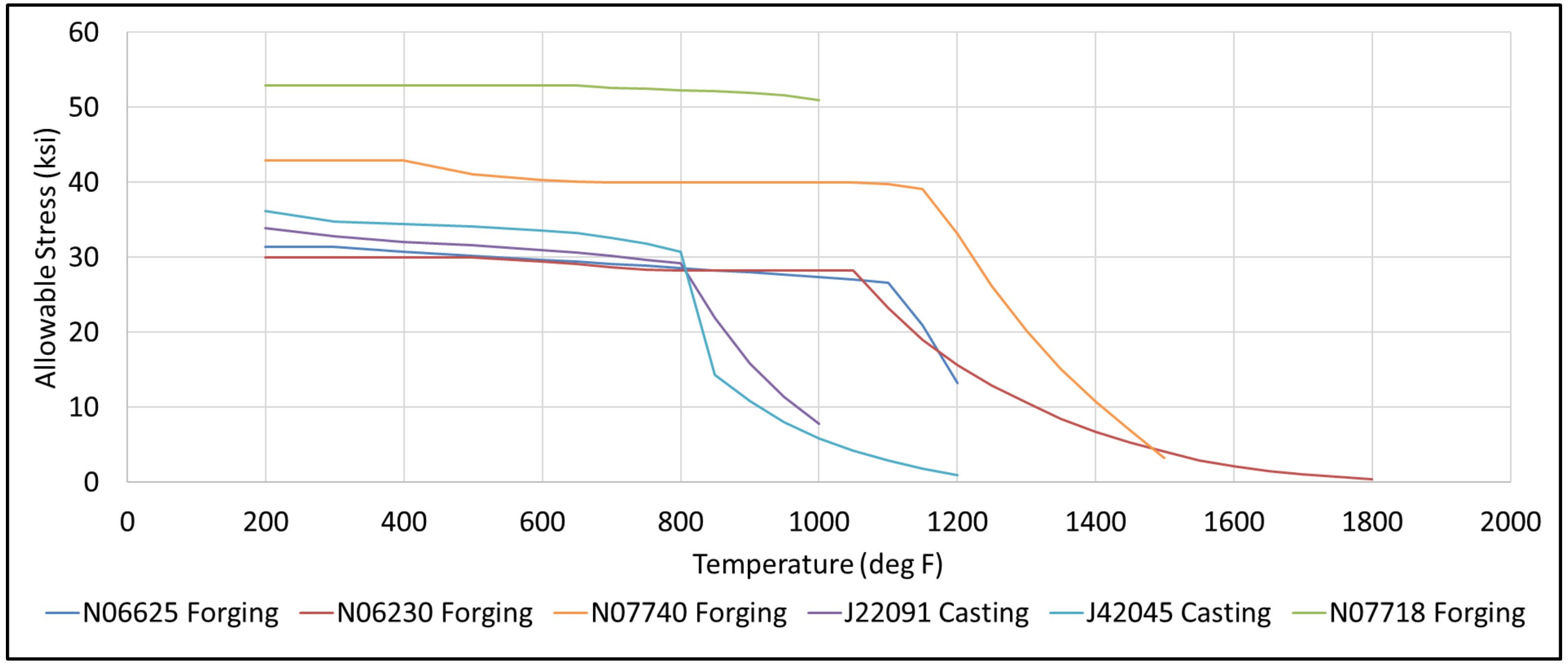
Matl	S_bolt_allow (psi)	Total Bolt Count																					Nut Diam
K14072.a	25100	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	in
Bolt Diameter	3	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	ps	ps	ps	ps	5.433
	3.25	s	s	s	s	s	s	s	s	s	s	s	s	s	s	ps	ps	ps	ps	ps	ps	ps	5.857
	3.5	s	s	s	s	s	s	s	s	s	s	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

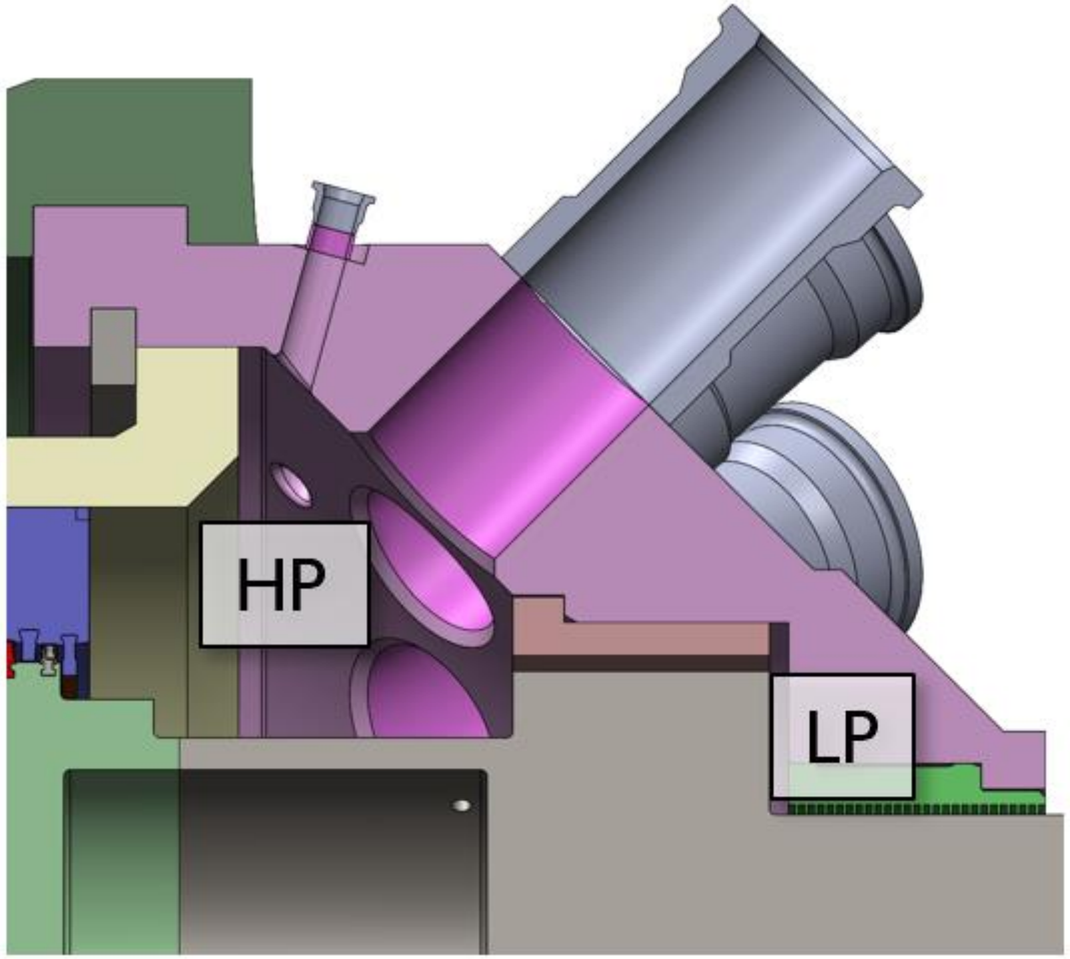
Outer case FEA



Combustor housing design

- ASME Section VIII, Div. 1 – UG-27, UG-32
  - Cylindrical Sections: $t = \frac{PR}{(SE - 0.6P)}$
  - Conical Section: $t = \frac{PD}{2\cos(\alpha)(SE - 0.6P)}$
- ASME Section VIII, Div. 2 – Part 4
  - Cylindrical Sections: $t = \frac{D}{2}\, exp\left(\left[\frac{P}{SE}\right] - 1\right)$
  - Conical Section: $t = \frac{D}{2\cos(\alpha)}\, exp\left(\left[\frac{P}{SE}\right] - 1\right)$

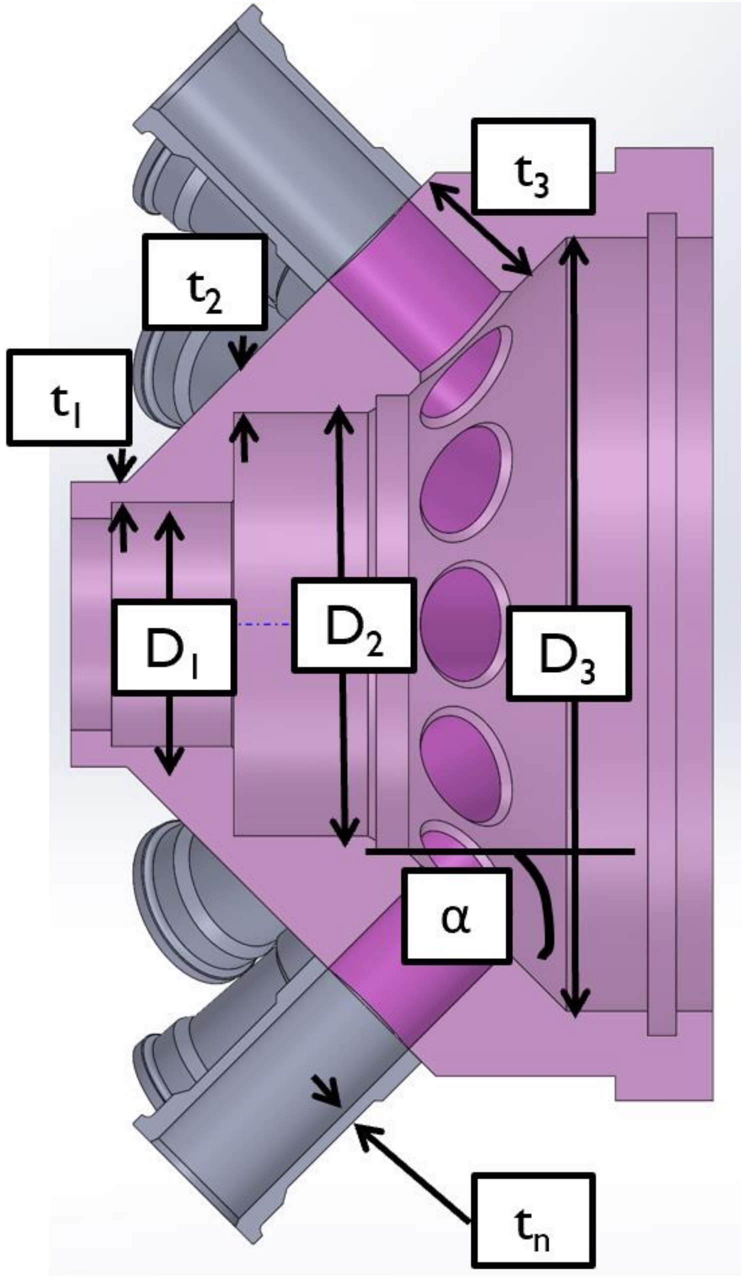




Combustor housing design

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

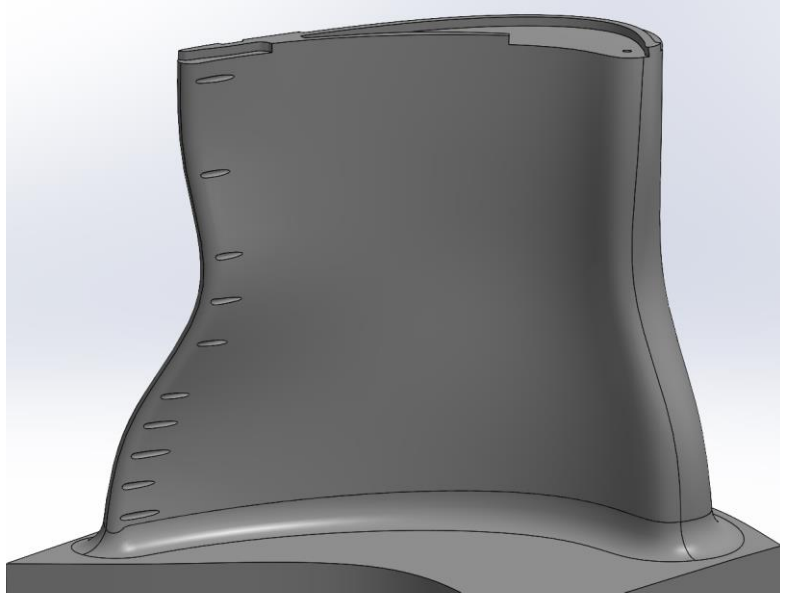
*conical section requires 1.5*thickness to accommodate 12 can holes

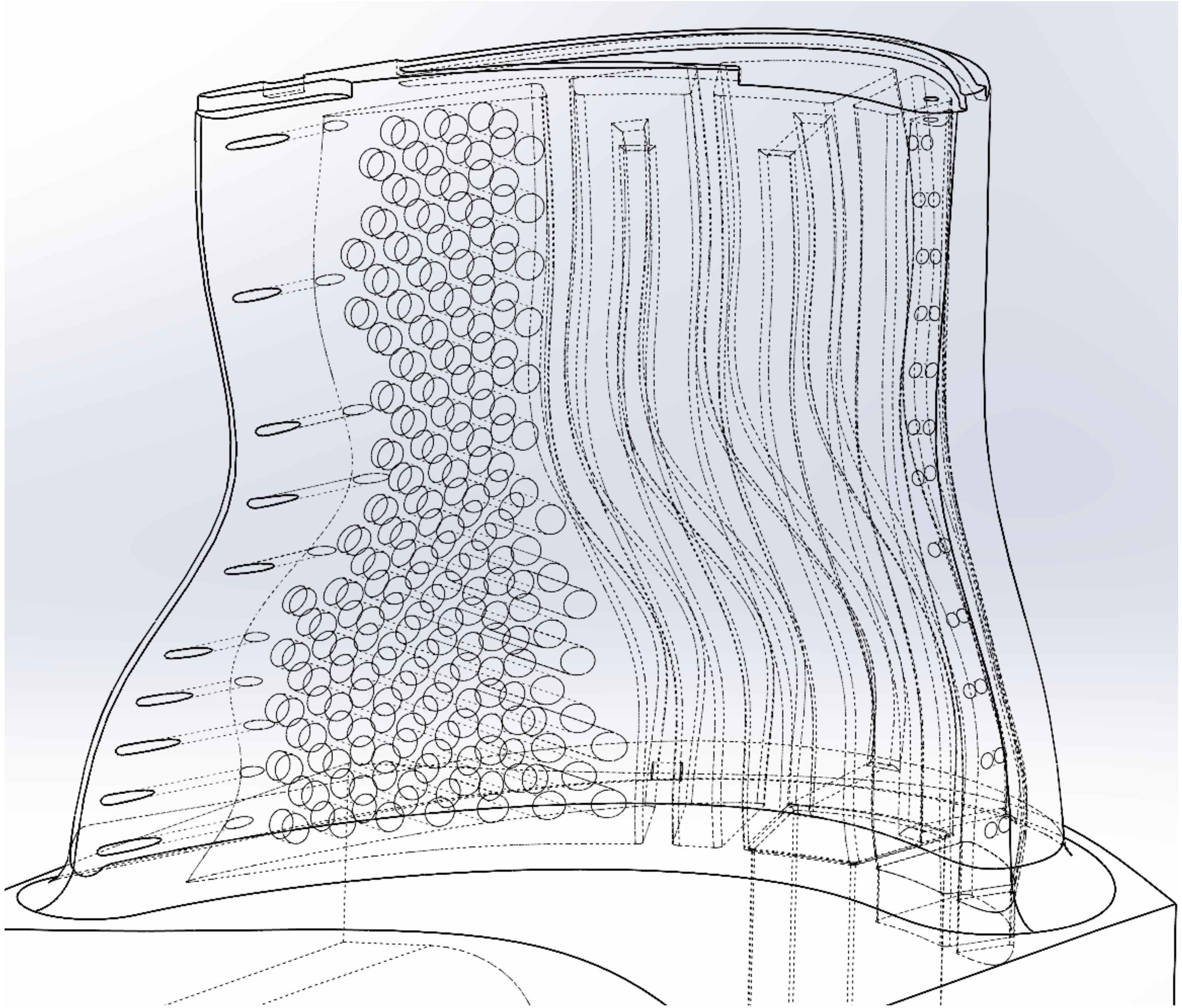


While N07718 requires the thinnest vessel sections, fabrication with low-Cr steels is more feasible. J42045 offers the best allowable stress at design temperature (800°F). Nozzle fabrication will be a Nickel alloy for high temperature application near nozzle.

S1B design

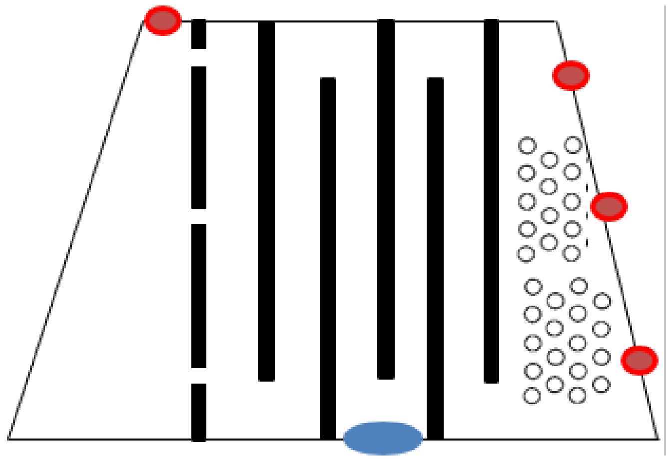
- Leading edge impingement
- Ribbed serpentine channels
  - Ribs not yet modeled
- Pin-fin array
- Trailing edge ejection
- Thermal Barrier Coating





S1B design – thermal and hydraulic network

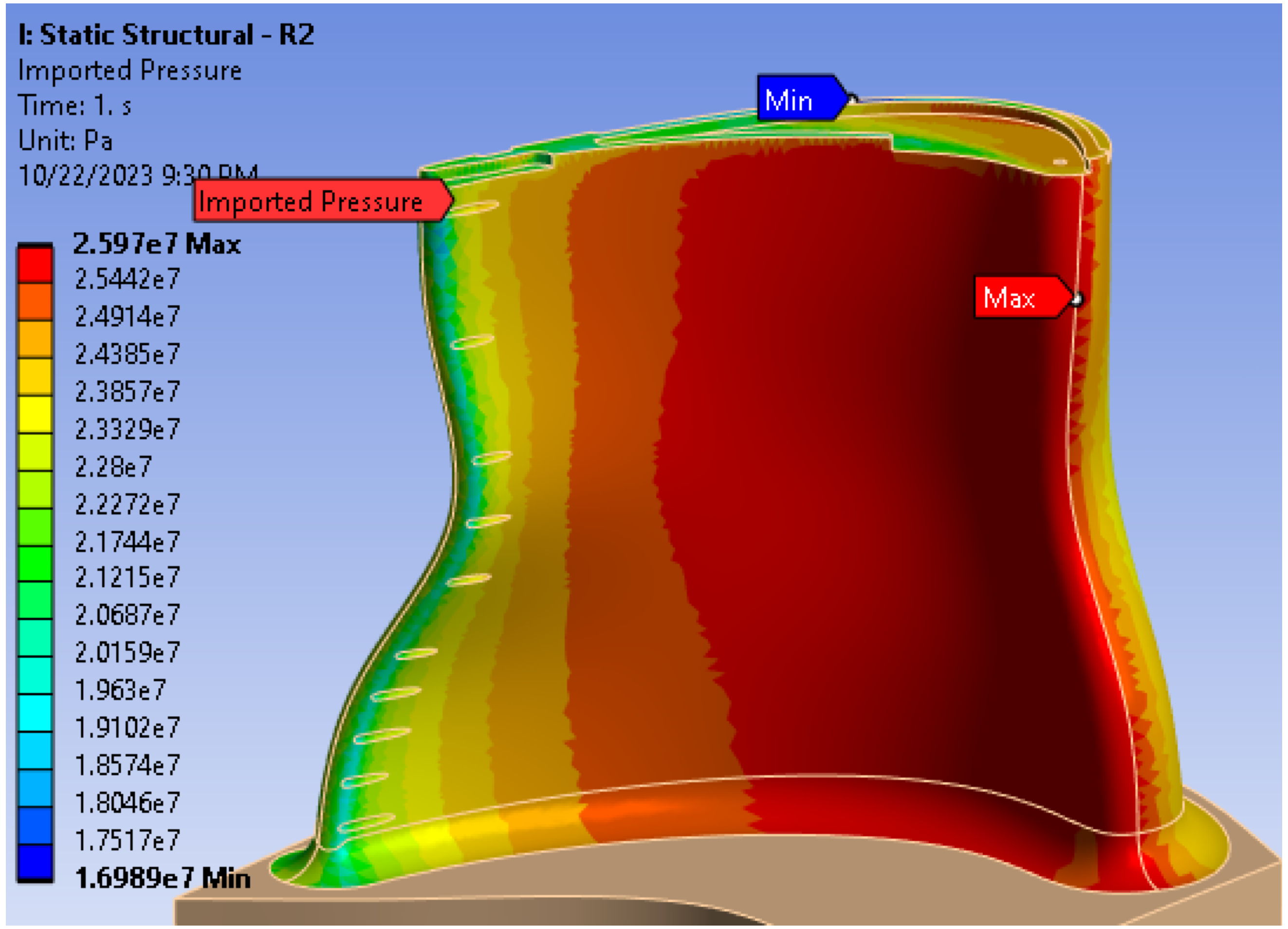
- Mass flow calculated from pressure differential and area at each flow ejection hole
  - Hole discharge coefficients from literature (Cd = 0.75)
  - Ribbed channels f/f0 = 10.
  - Pin fin array friction factor of 0.2 per row.
  - Significant centrifugal "pumping" with CO_2 cooling flow.



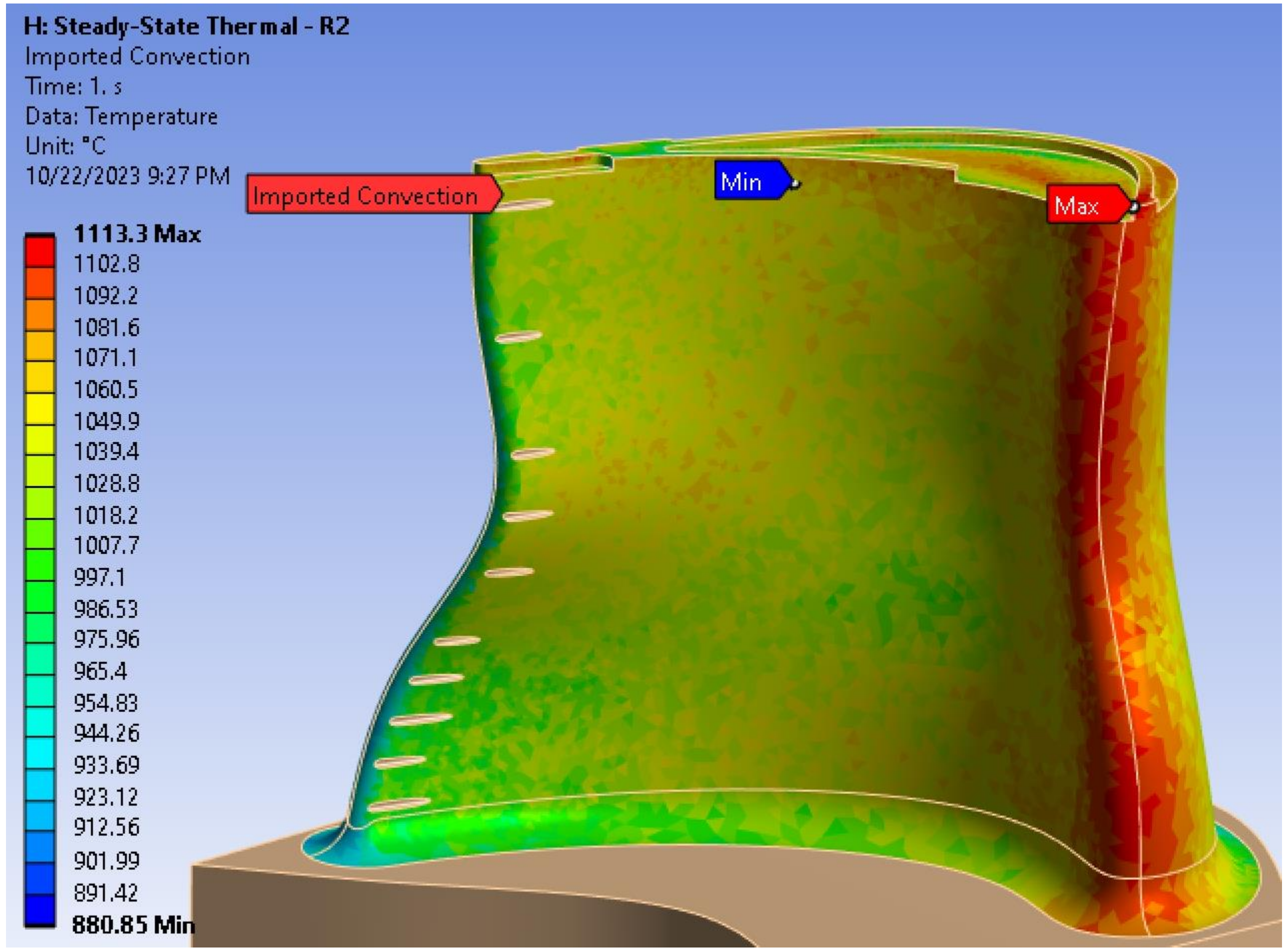
- Thermal resistance network used to estimate blade surface Temperature.
  - LE Impingement HTC determined from Chupp correlation.
  - Serpentine channel HTC from modified Gnielinski correlation with BP2 test data enhancement factor.
  - TE pin-fin array HTC from Metzger correlation
  - Thermal Barrier 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**

S1B design – imported CFD results

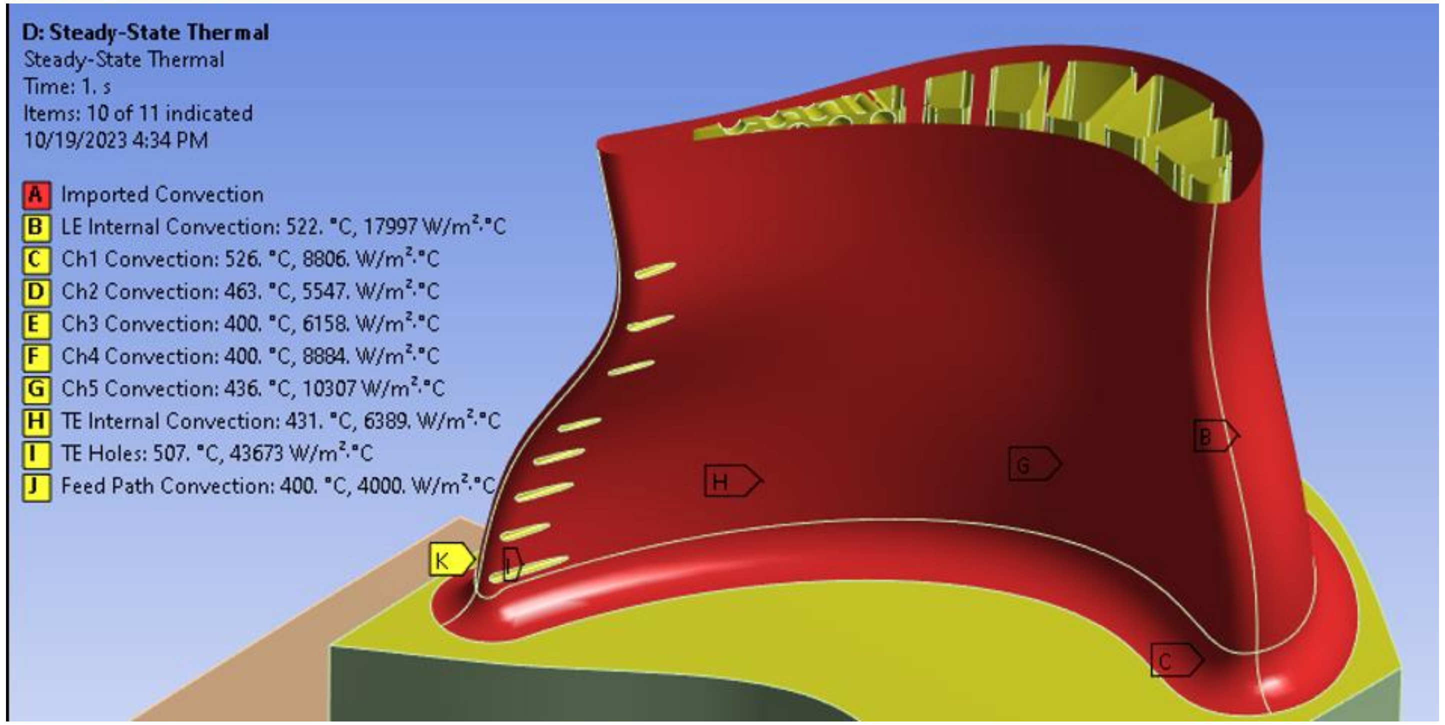


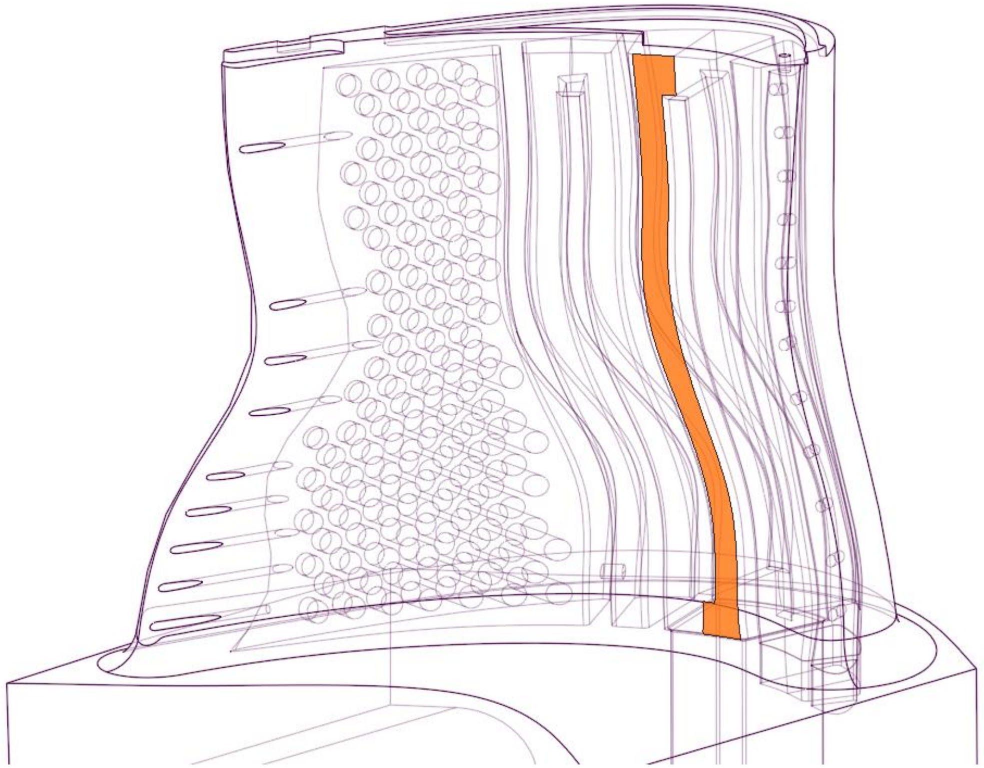
Imported pressure loading.



Imported convection source temperature for external heat load.

S1B design – thermal FEA



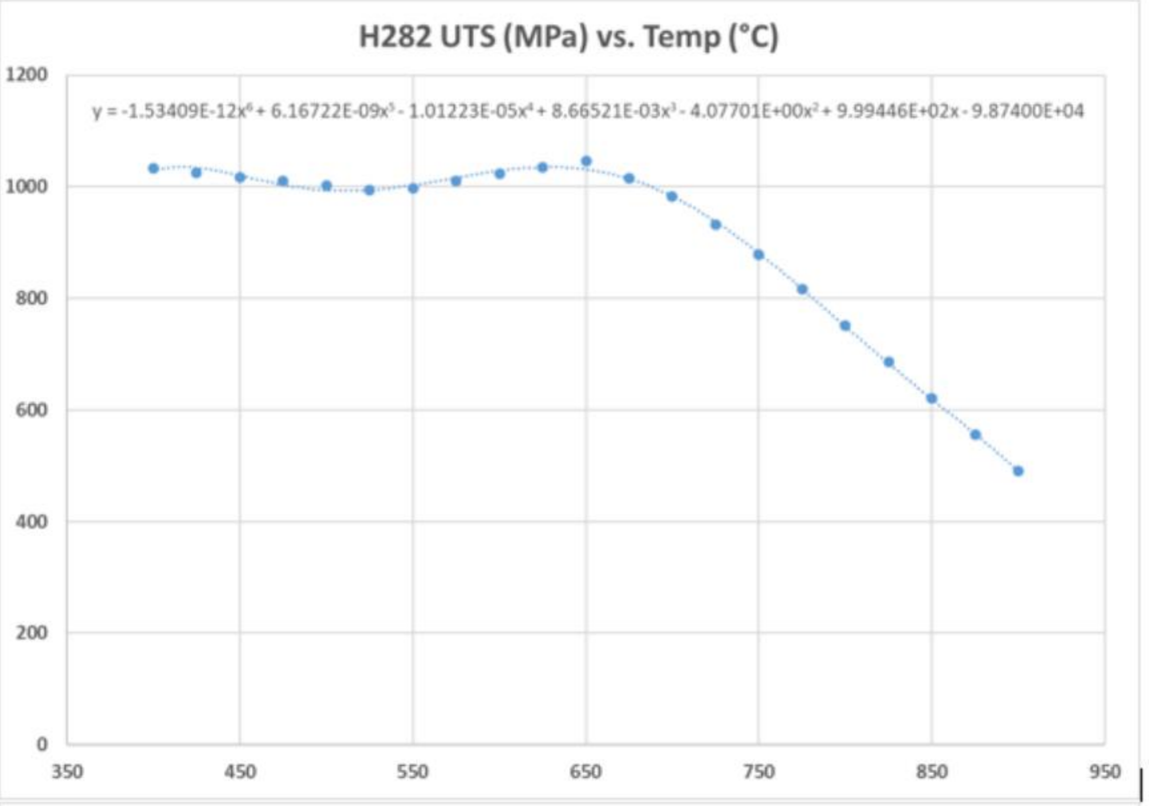


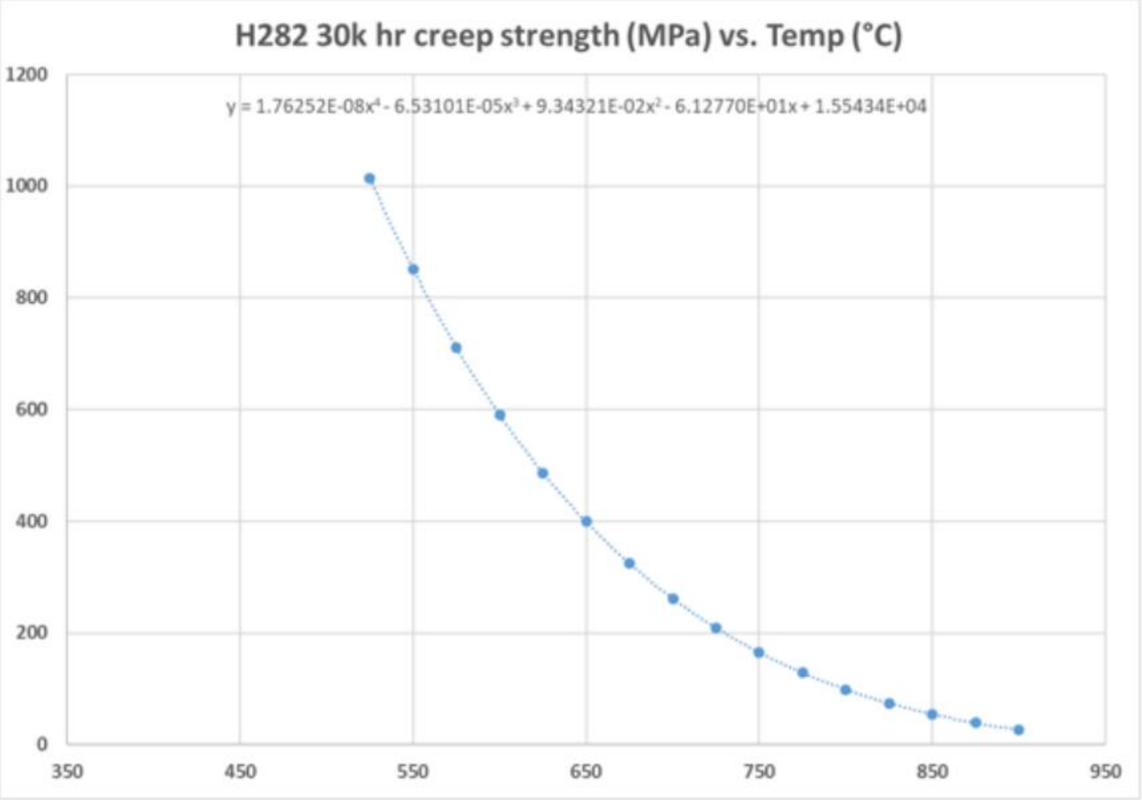
- Each internal passage is given a unique cooling CO_2 temperature and heat transfer coefficient.
- An approximate 100°C temperature rise is predicted from feed passage to LE and TE cavities.

S1B design - structural

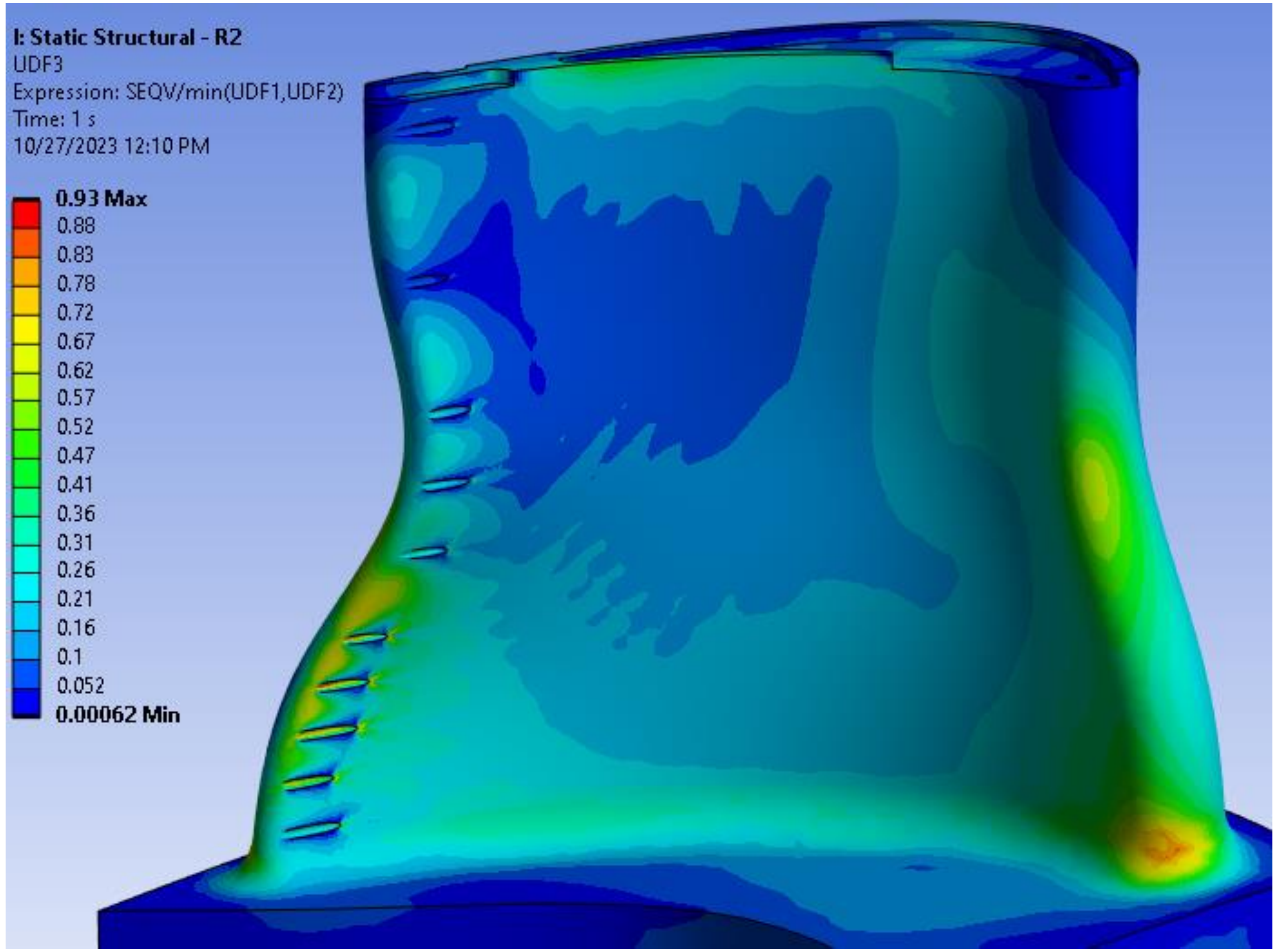
- Curve fits are produced for Haynes 282 UTS and 30k hour creep strength as a function of temperature.
- Result for initial evaluation:

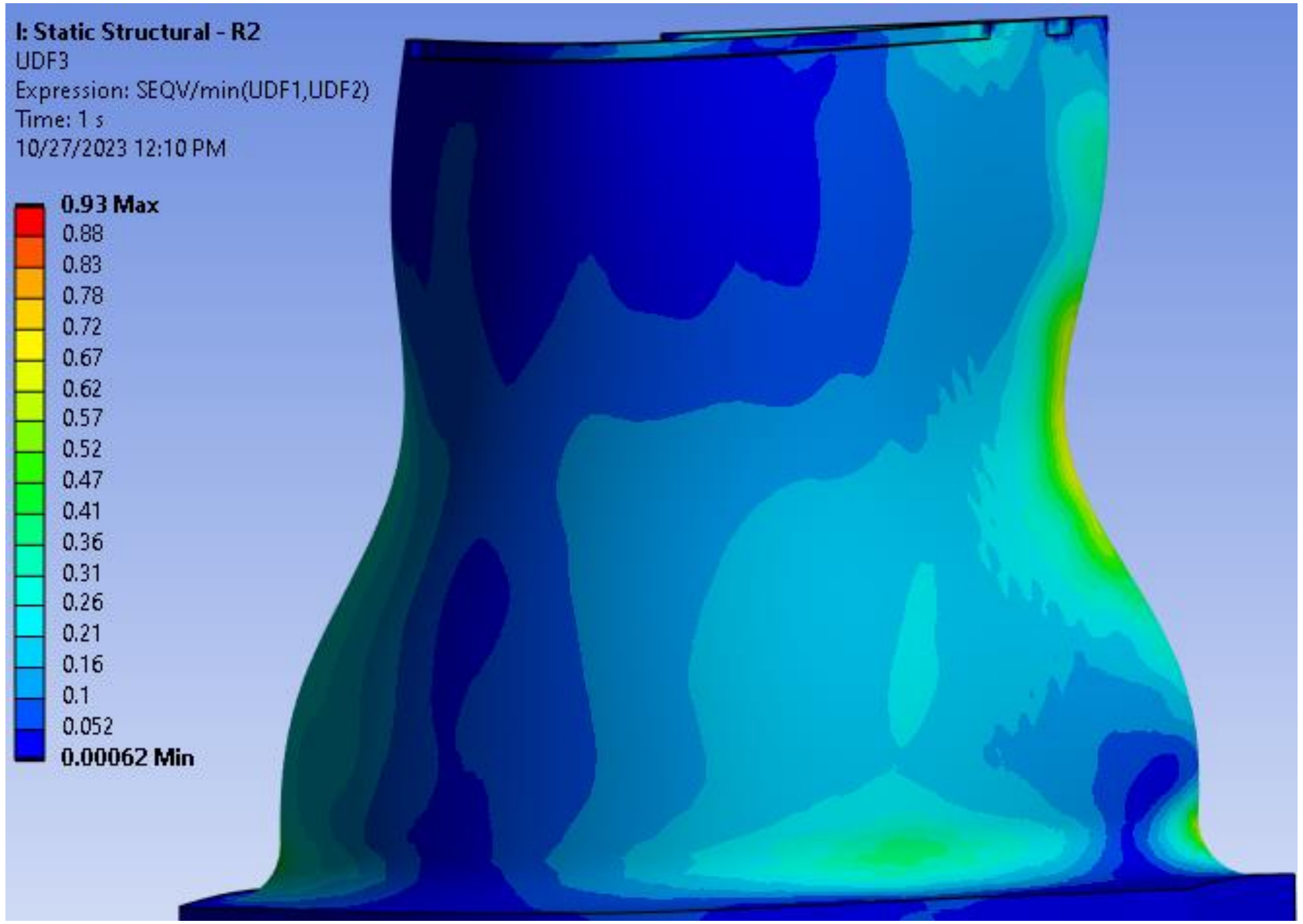
$$f = \frac{\sigma_{VM}}{\min(UTS(T), \sigma_{cr}(T))}$$





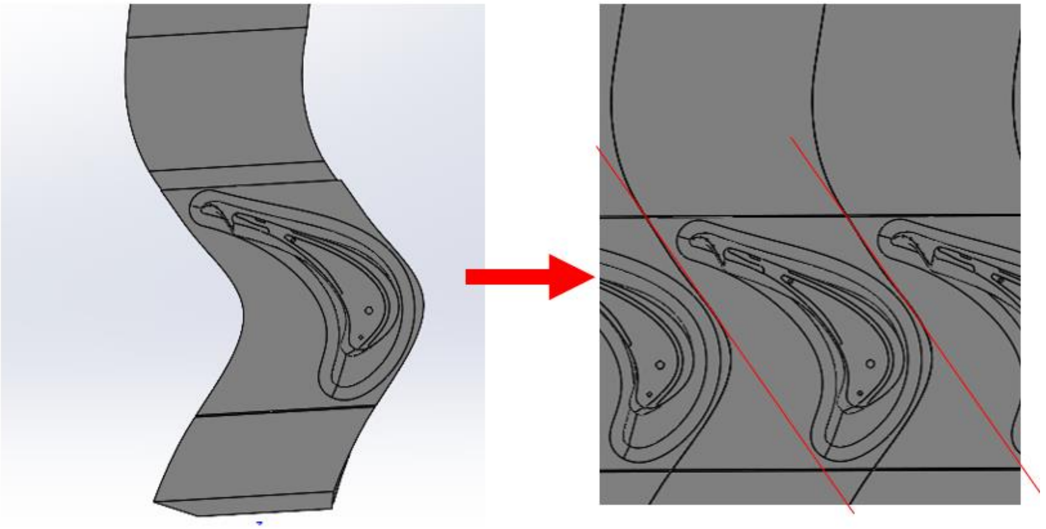
S1B design – structural FEA

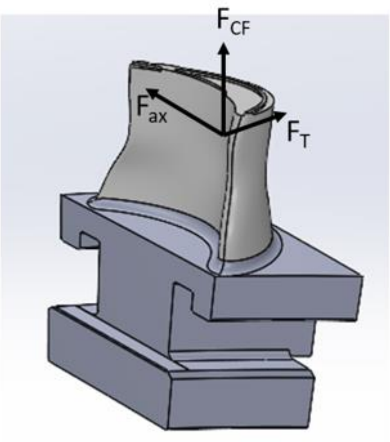


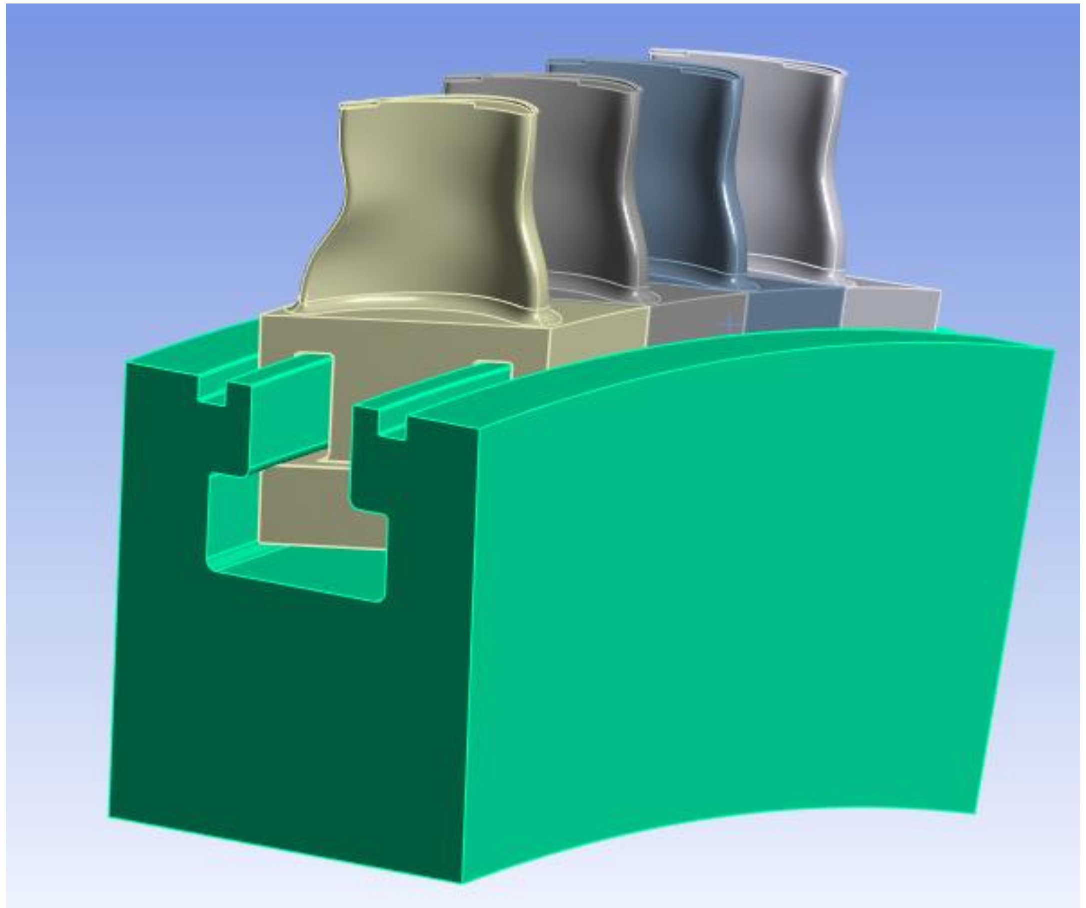


$$f = \frac{\sigma_{VM}}{\min(UTS(T), \sigma_{cr}(T))}$$

S1B blade root design



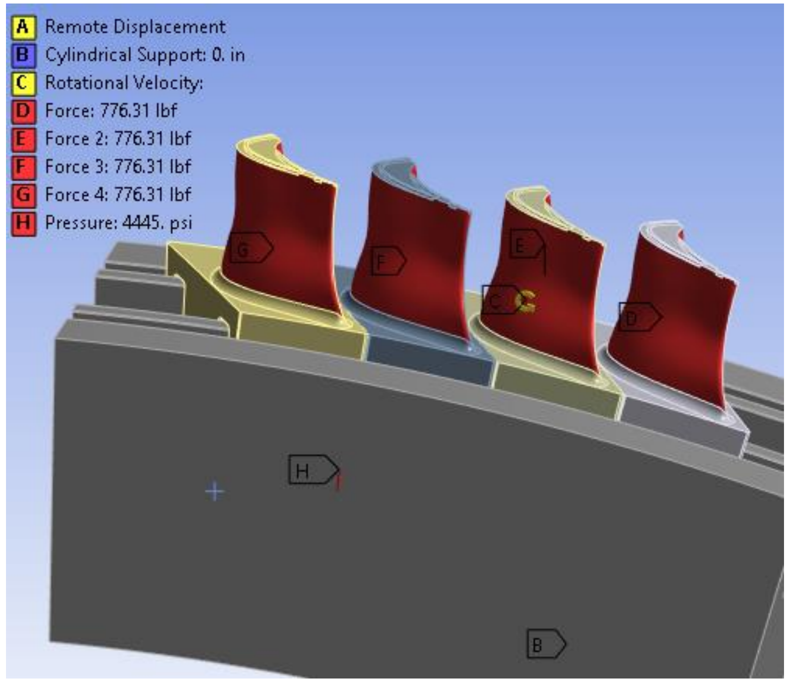




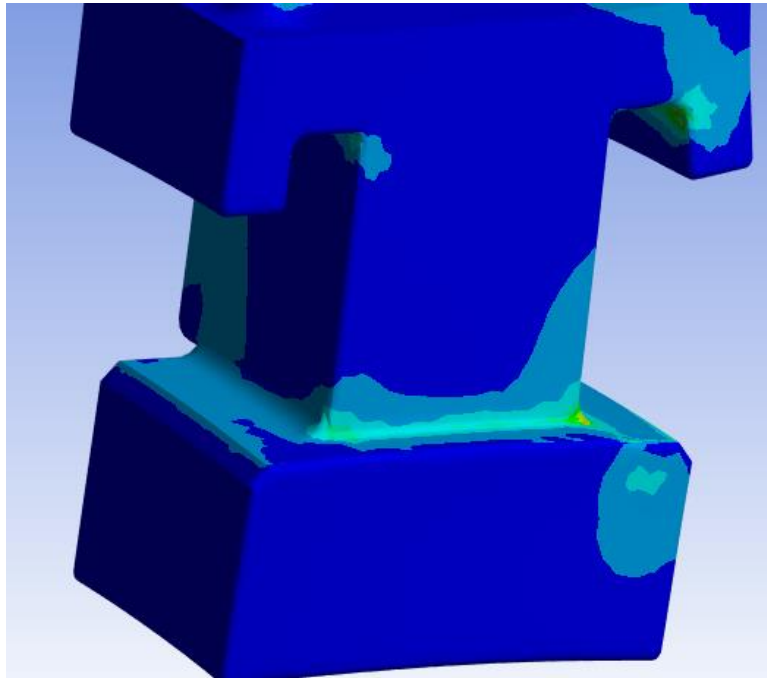
- Parallel T-root chosen for monolithic rotor based on literature study.
- Sidestep on base of T-root allows for blades to load off of each other.

S1B blade root design

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

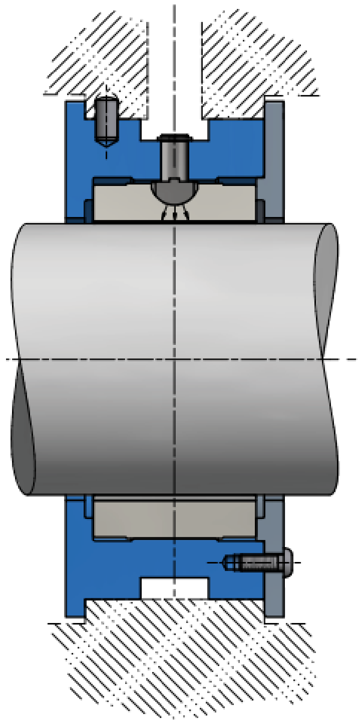


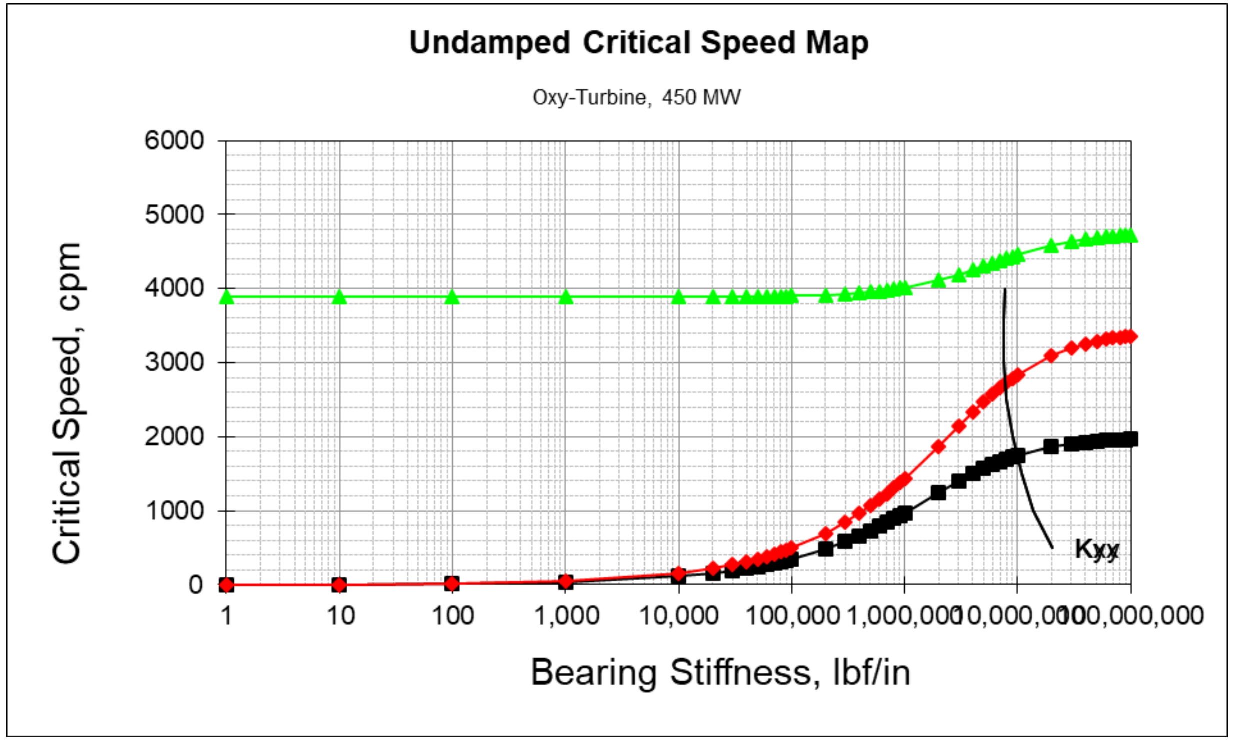
		Rotor Thrust		Tangential Force	
	Count	Total	Per Blade	Total	Per Blade
	#	lbf	lbf	lbf	lbf
Blade 1	142	82,351	579.9	73,259	515.9
Blade 2	142	87,750	618.0	74,212	522.6
Blade 3	142	81,806	576.1	75,217	529.7
Blade 4	126	70,228	557.4	74,498	591.3
Blade 5	126	55,424	439.9	72,064	571.9
Blade 6	126	37,759	299.7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

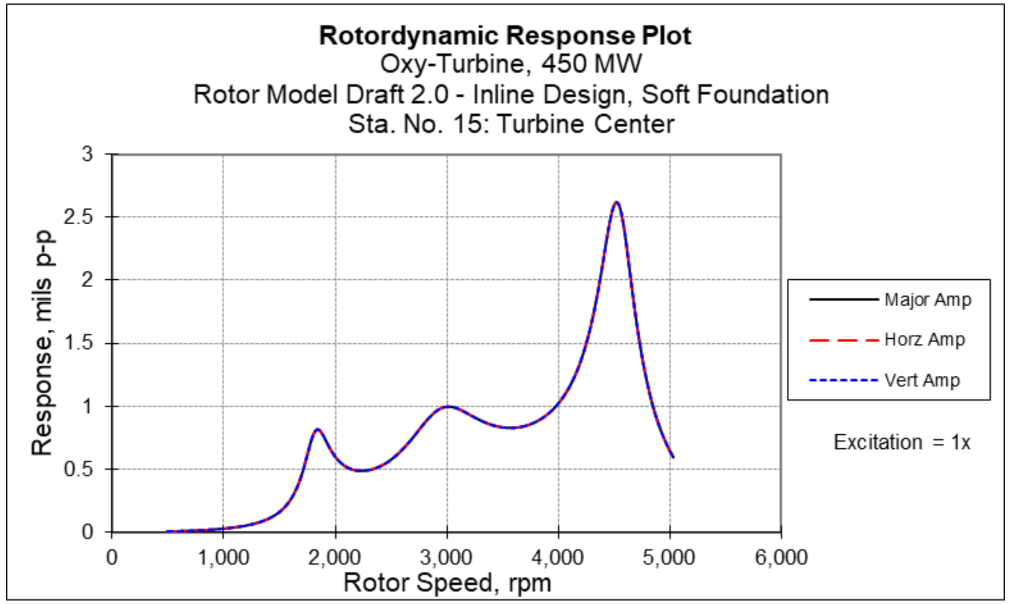


Bearing specification

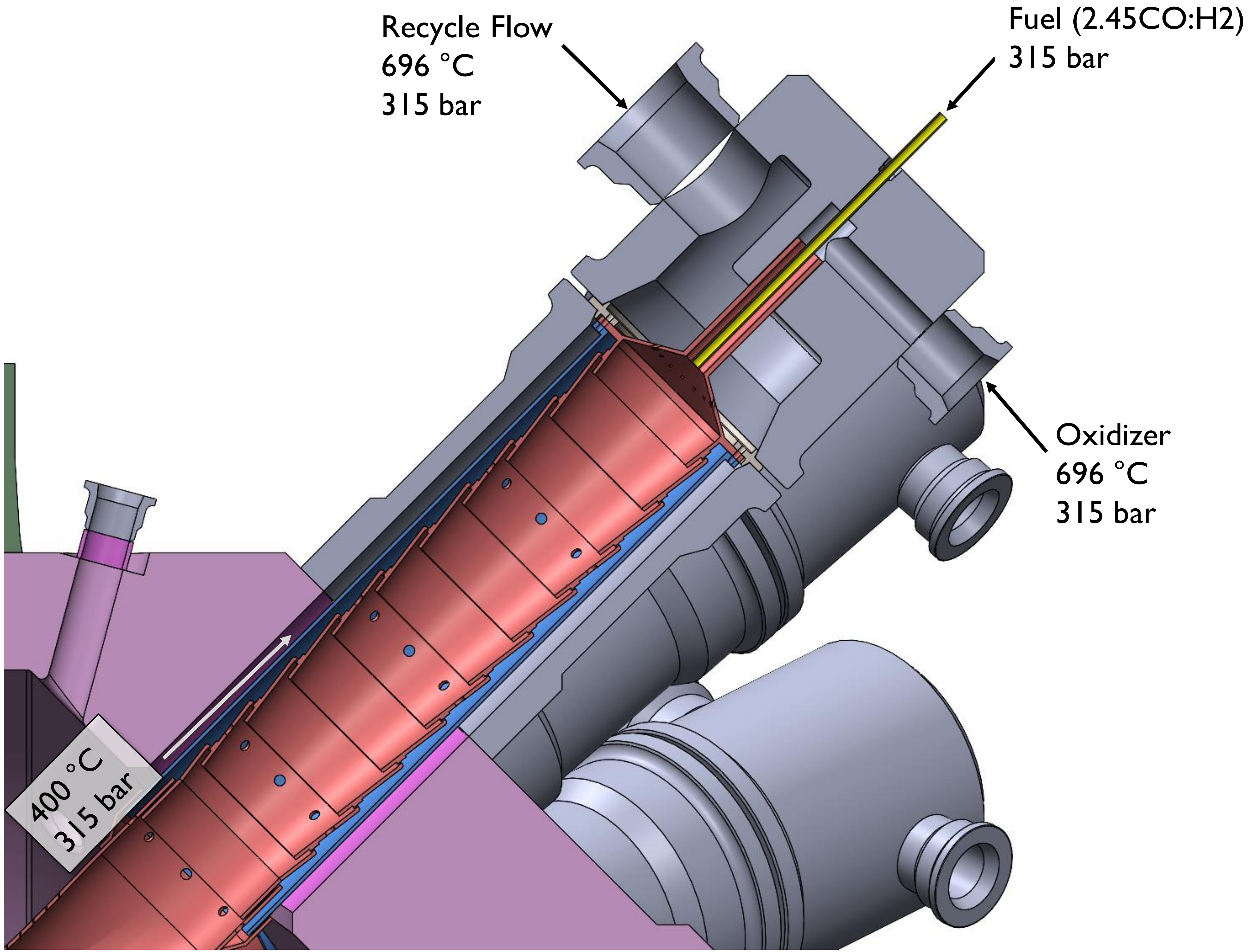
- Radial bearings were sized with assistance from a vendor for the 21" shaft diameter (175 GPM per bearing).
- Updated rotordynamic analysis shows acceptable response and margin from running speed (3600 RPM).


Flange Located Type
Split Bearing - Code/2DF



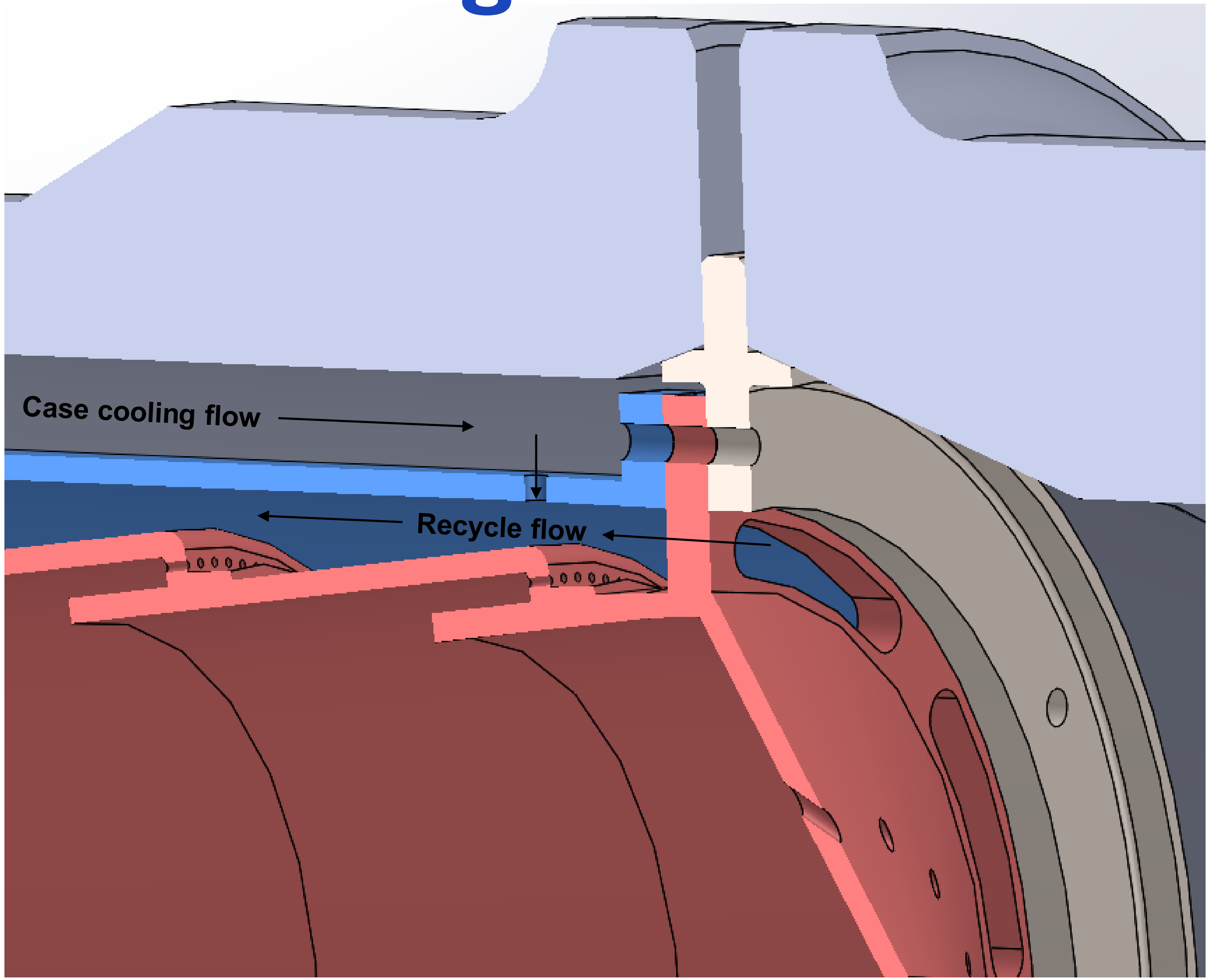


Combustor Design



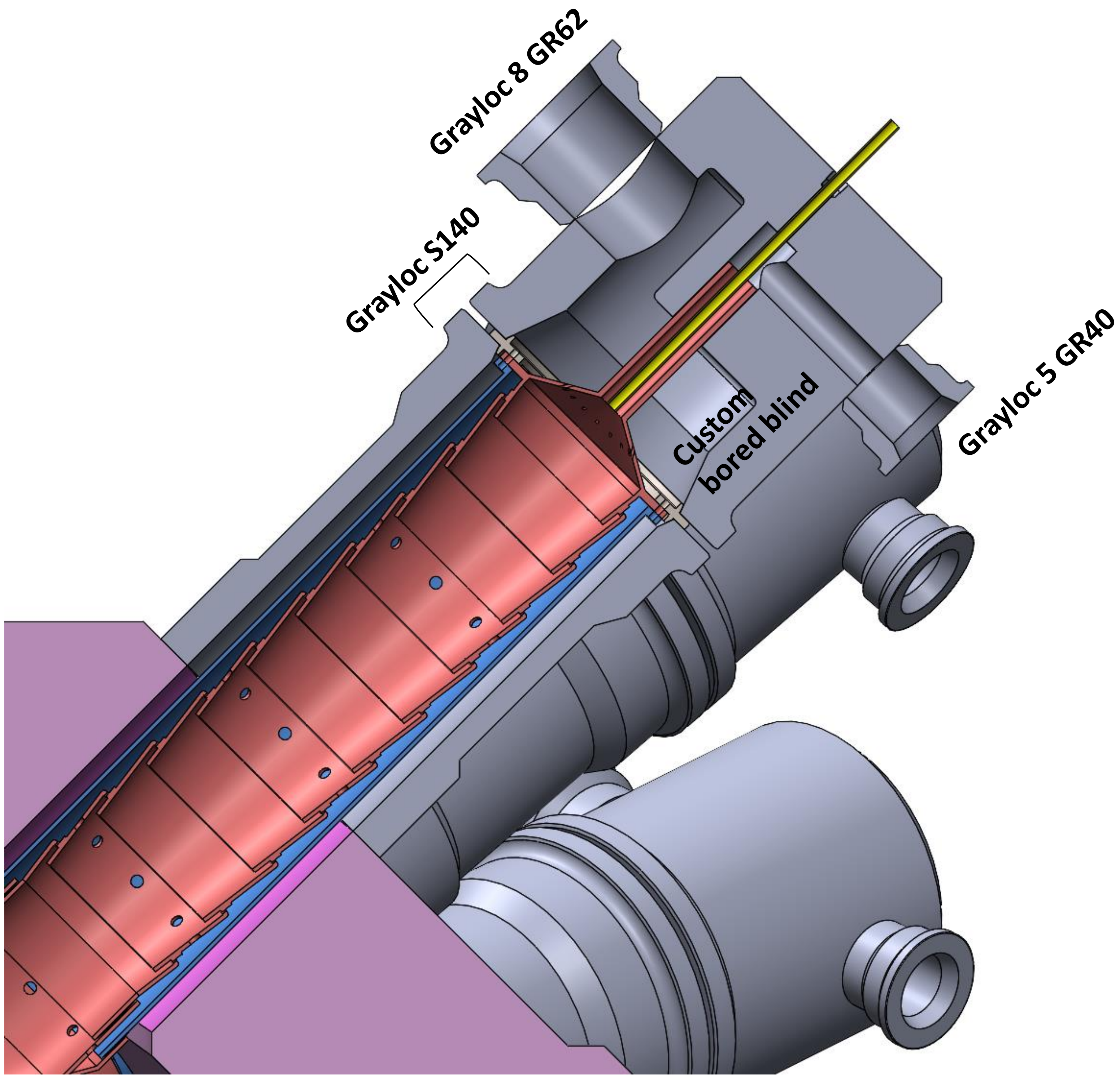
Combustor thermal management

- 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.



Combustor Design

- Recycle flow temperature and pressure (696 °C, 315 bar) mandates the use of nickel alloy (IN 740H, 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.



BP3 Continuing Activities

- Thermal and aerodynamic validation of S1B design at SwRI and Purdue test facilities, respectively.
- Cost estimation for turbine design, to be integrated into EPRI technoeconomic analysis.
- Thermodynamic cycle reevaluation based on determined cooling flow requirements.

Publications

- 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?