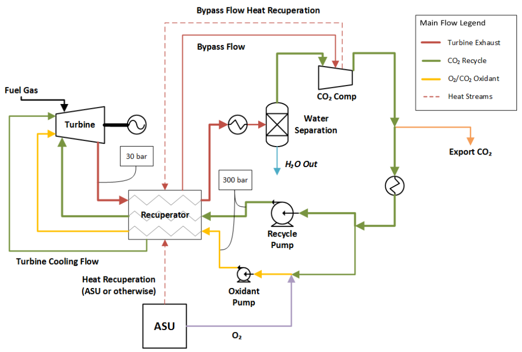
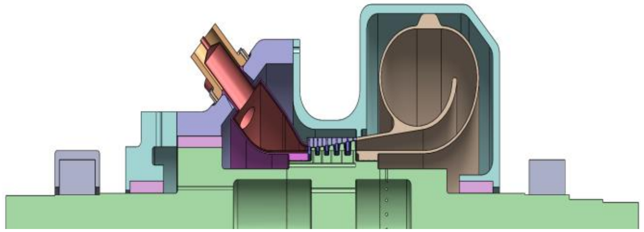
Development of Oxy-Fuel Combustion Turbines with CO_2 Dilution for Supercritical Carbon Dioxide Based Power Cycles

University Turbine Systems Research Project Review Meeting



Jeff Moore, Ph.D.
Institute Engineer
Southwest Research Institute



DE-FE0031620
SwRI Project 23916

NETL PM: Seth Lawson
2019 UTSR Project Review Meeting
Nov. 5-7, 2019

SwRI is a contract R&D company

- Performing R&D for commercial and government clients over 70 years
- Nonprofit corporation – 501(c)(3)
  - 100% contract revenue
  - Internal R&D, new facilities
- $500M-600M USD annual gross revenue
- Over 2,600 employees
- Over 1,200-acre campus
- Over 2.3 million ft^2 of laboratories & offices

Aerial view of SwRI campus in San Antonio, TX

"From deep sea to deep space and everything in between"

Team Members

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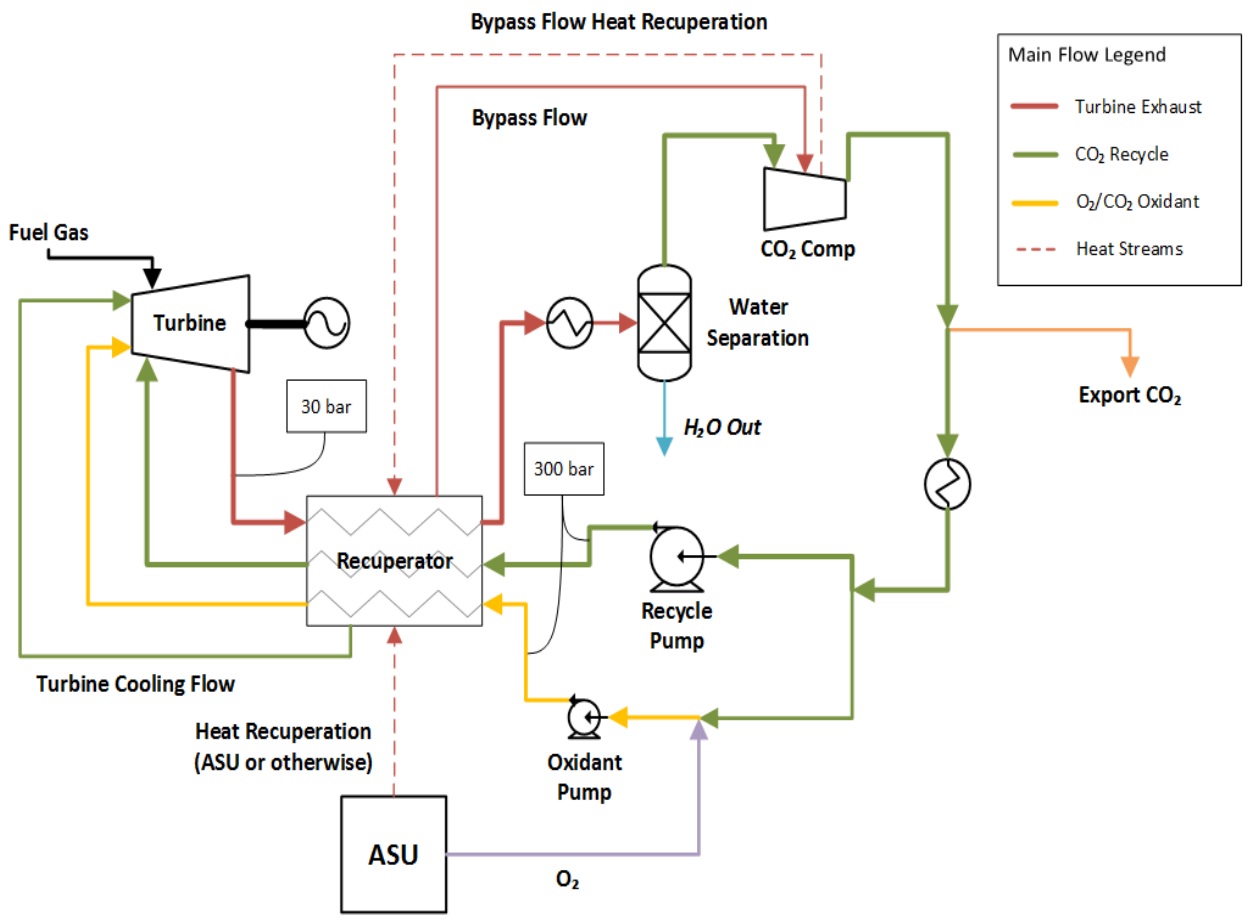
Project Objectives

- Develop a conceptual design for a sCO2, coal syngas or natural gas-fired oxy-fuel turbine in the 150-300 MWe size range capable of 1200°C turbine inlet temperature at 30 MPa and exhaust temperatures in the 725-775°C range.
- Significantly improve the state-of-the-art for thermal efficiency and results in a high-pressure stream of CO_2 simplifying carbon capture, making the power plant emission-free.

sCO_2-based, semi-closed recuperated Brayton (Allam) cycle Process Flow Diagram



From the FOA

- The Phase I development effort must conceptually address the full oxy-combustion turbine design including:
  - Combustor, turbine stage count, airfoil design, airfoil cooling, hot gas path, exhaust thermal management, seals, bearings, machine housing/casing, machine/rotor dynamics, thrust management, instrumentation and controls and all other major subsystems.

From the FOA

- Phase I work will identify technology gaps and a detailed test plan to address these gaps through bench scale testing in a potential subsequent Phase II project.
- The test plan, and associated Phase II testing, should resolve key technical uncertainties to support a Phase II preliminary design.

Phase 1: Technical Approach

- Develop a conceptual oxy-fuel sCO_2 combustion turbine design: SwRI and GE (Aero, mechanical, thermal management), Air Liquide (combustor), EPRI (materials), and Georgia Tech (combustion kinetics).
- Develop a thermodynamic cycle analysis (heat, mass, and energy balance) for a sCO_2 semi-closed recuperated Brayton cycle based on natural gas, as the fuel and the proposed sCO_2 turbine: 8 Rivers.
- Consistent with the conceptual design and cycle analysis, develop nominal engine component boundary conditions in terms of pressures, temperatures, mass flows, heat flux etc.: 8 Rivers, GE and SwRI.

Phase 1: Technical Approach

- Consistent with the conceptual design and cycle analysis, develop and evaluate overall engine turbine aerodynamics, combustor, mechanical layout, thermal management options and concepts including engine cooling fluids, air foil thermal management, exhaust thermal management etc.
- Develop a Technology Maturation Plan (TMP) leading to pre-commercial testing of the proposed oxy-fuel sCO_2 combustion turbine
- Develop a Test Plan with cost, schedule, and resources required to resolve identified technology gaps and that supports the advancement of a potential Phase II Preliminary Design

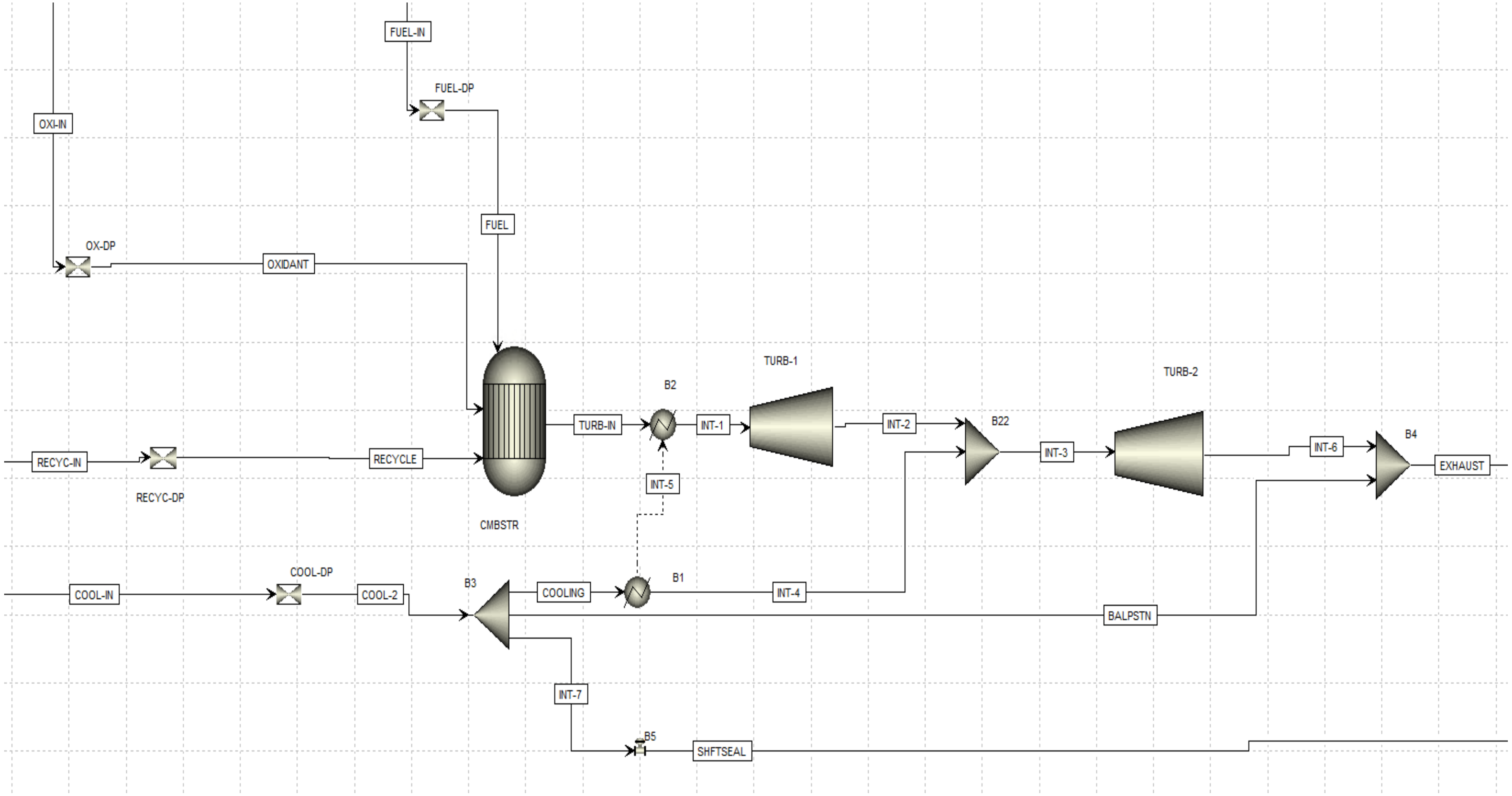
Preliminary Technical Assessment

- Literature Review Performed
  - Including NetPower project and Toshiba turbine development
- Cycle Modeling
  - Selected 300 MWe Frame Size
  - Compare against prior work done for future scaled NetPower project
  - Modeling will begin with pure methane with simplified model for turbine cooling

Cycle Modeling Assumptions

- Turbine modelled with a 90% isentropic efficiency.
- Turbine split into two to allow the introduction of cooling flow in between models.
- Two turbine models produce equal power.
- 10% of the main recycle flow is diverted to provide the cooling flow and is provided at 430°C
- Cooling flow is heated to 800°C internal to the turbine; this is modelled by using heat from the main flow before it enters the first turbine.
- Cooling flow is expanded to intermediate pressure during mixing with a main gas path between the two turbine models.
- Gibbs equilibrium reactor used for the combustor (i.e., reaction rates are not taken into account).
- The turbine inlet temperature is 1,200°C.
- Turbine inlet pressure is 305 bar, with an exhaust pressure of 30 bar.
- All streams entering the combustion turbine experience approximately a 3% pressure loss through the combustor.
- The equation-of-state used is Soave-Redlich-Kwong.

ASPEN Cycle Model



Preliminary Cycle Modeling

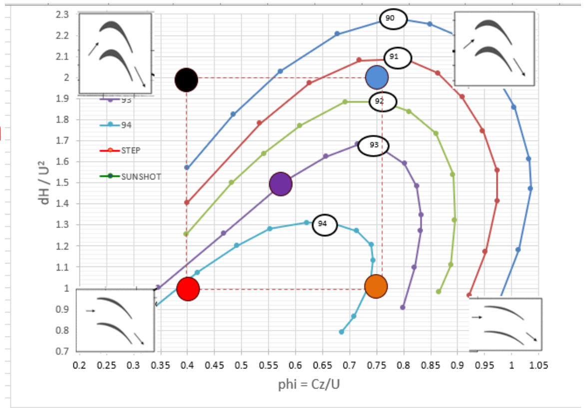
	COOL-IN	COOLING	FUEL-IN	FUEL	OXI-IN	OXIDANT	RECYC-IN	RECYCLE	TURB-IN	EXHAUST
Substream: MIXED										
Mole Flow kmol/hr										
CH4	0	0	2436.61	2436.61	0	0	0	0	2.58E-22	2.58E-22
O2	40.7438	40.7438	0	0	5024.019	5024.019	366.6942	366.6942	517.4953	558.2391
AR	51.58562	51.58562	0	0	190.9455	190.9455	464.2706	464.2706	655.2161	706.8017
CO	0.010801	0.010801	0	0	0.034832	0.034832	0.097208	0.097208	0.137188	0.147989
H2	0.000336	0.000336	0	0	0.001084	0.001084	0.003025	0.003025	0.004269	0.004605
CO2	5106.204	5106.204	0	0	16467.09	16467.09	45955.83	45955.83	64859.53	69965.74
H2O	3.286727	3.286727	0	0	10.59943	10.59943	29.58054	29.58054	4913.4	4916.687
Mass Flow kg/hr										
CH4	0	0	39089.95	39089.95	0	0	0	0	4.14E-21	4.14E-21
O2	1303.753	1303.753	0	0	160763	160763	11733.77	11733.77	16559.23	17862.98
AR	2060.742	2060.742	0	0	7627.891	7627.891	18546.68	18546.68	26174.57	28235.32
CO	0.302536	0.302536	0	0	0.975654	0.975654	2.722823	2.722823	3.8427	4.145236
H2	0.000678	0.000678	0	0	0.002185	0.002185	0.006098	0.006098	0.008606	0.009284
CO2	224723	224723	0	0	724714	724714	2022510	2022510	2854460	3079180
H2O	59.21131	59.21131	0	0	190.9517	190.9517	532.9018	532.9018	88516.29	88575.5
Total Flow kmol/hr	5201.831	5201.831	2436.61	2436.61	21692.69	21692.69	46816.48	46816.48	70945.79	76147.62
Total Flow kg/hr	228147	228147	39089.95	39089.95	893296	893296	2053320	2053320	2985710	3213860
Total Flow cum/hr	1043.836	1073.55	226.2845	231.2627	6348.024	6538.998	13745.19	14156.04	30544.29	223808
Temperature C	430	429.5408	72.06623	71.4434	739	739.2248	739	739.1531	1200.009	778.3606
Pressure bar	316.5	306.5	315	305	315	305	315	305	305	30

- Current cycle thermal efficiency is 58%, which includes the air separation unit (ASU) and on an low heating value (LHV) basis.

Preliminary Turbine Sizing

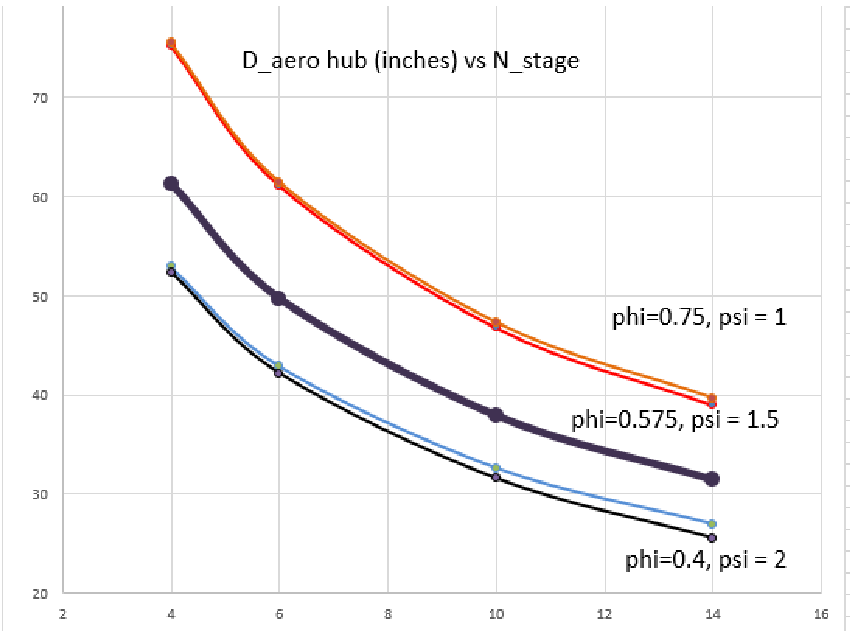
Step1: Simple 0D Calcs for Preliminary Sizing… (Step2=> 2D layout; Step3=> detailed 3D design)

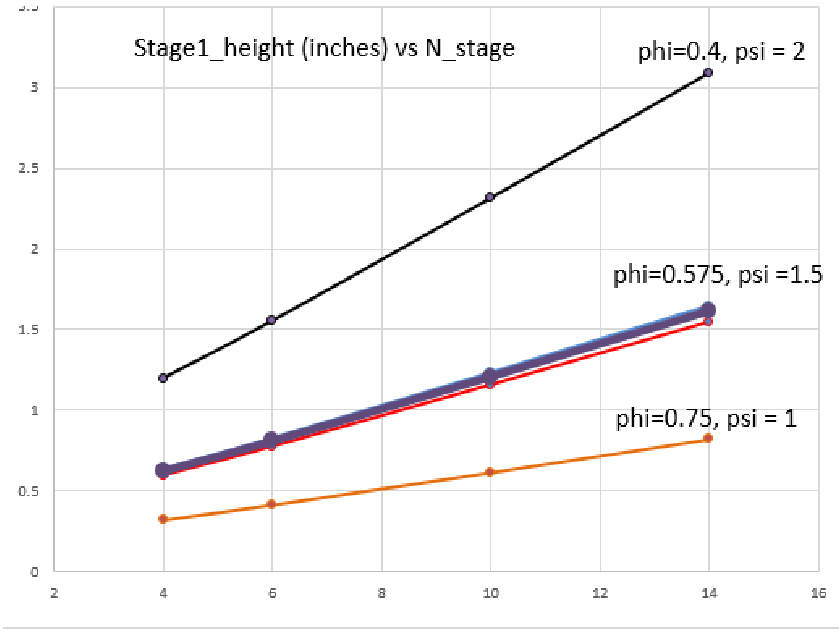
- REFPROP gas property tables
- Pick locations on Smith's chart for 1st stage…
  - Compute stage Height & Hub diameter for a given stage count… 1st stage height ~1 inch
  - Gives a good picture of what to expect for more detailed layout design



Only a starting guide… various design/Efficiency/Size/Mechanical constraints play significant roles in placing Individual stages on Smith's chart

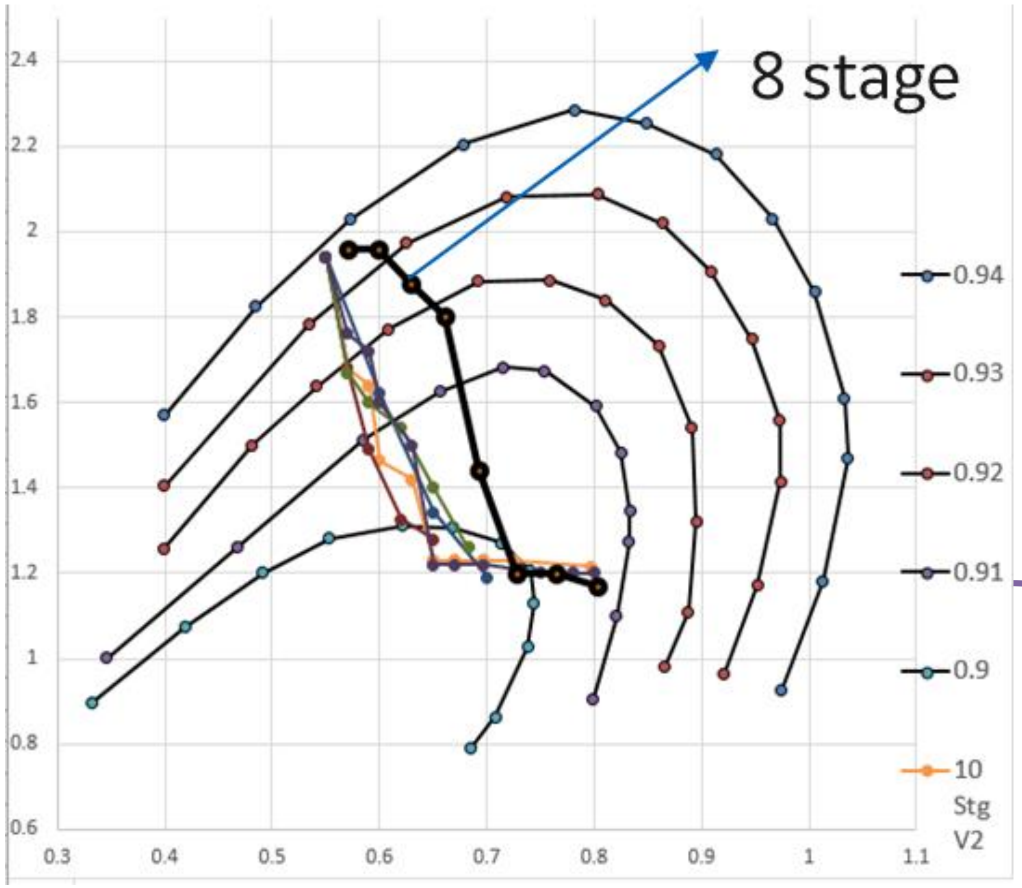
Examples…
~ 12~14 stages for a 30 inches Aero-Hub Diameter… 1st stage height ~1.5 inches
~ 6 stages for a 50 inches Aero-Hub Diameter… 1st stage height ~1 inches



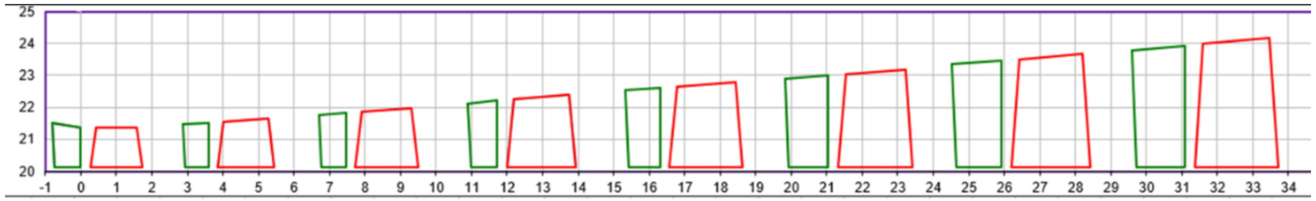


Preliminary Turbine Sizing

Step2: An Example…

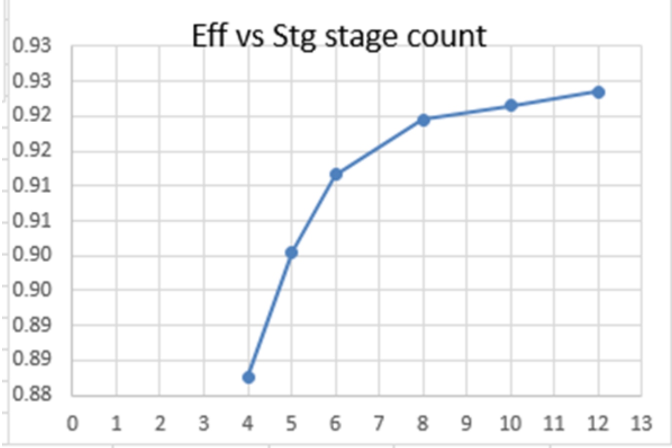


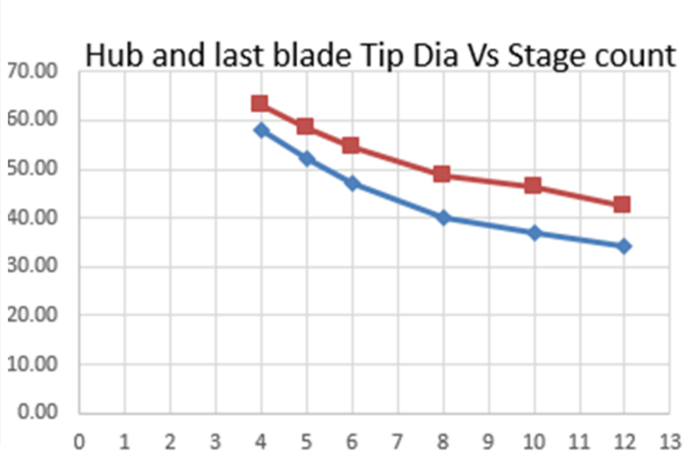
Various stages of a potential 6-stage design (~50 inches hub-dia) could look like this on Smith's chart

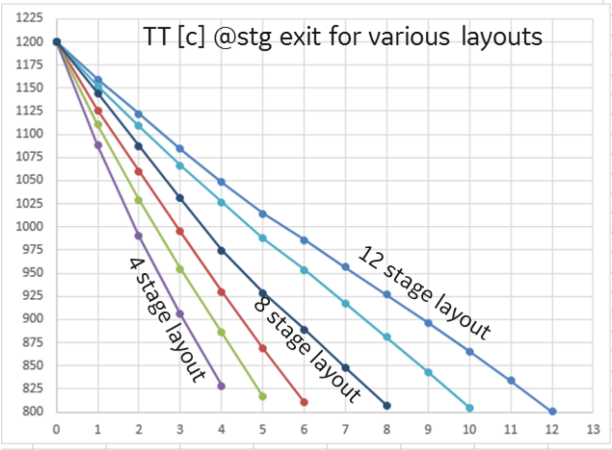


Preliminary Turbine Sizing

Single Flow Layout Option Evaluations: (a) Flow-path Efficiency, Aero-hub Diameter and Last-stage Tip Diameter Variations with Stage-count Selection; (b) Temperature Drop Along Turbine







Preliminary Turbine Sizing

	Single Flow Turbine						Double/Split Flow Turbine
Stage-Count	4-Stage	5-Stage	6-Stage	8-Stage	10-Stage	12-Stage	12-Stage
Aero Hub Diameter (Inches)	58	52	47	40.25	37	34	34.5
Shaft Total-Total Efficiency	88.3	90	91.1	92	92.1	92.3	92.1
Blade-count/Stage	142	142	142	142	96	96	140
Turbine Length (Inches)	21	22	24	35	40	43	40

More stages result in higher efficiency but more blades require more cooling flow

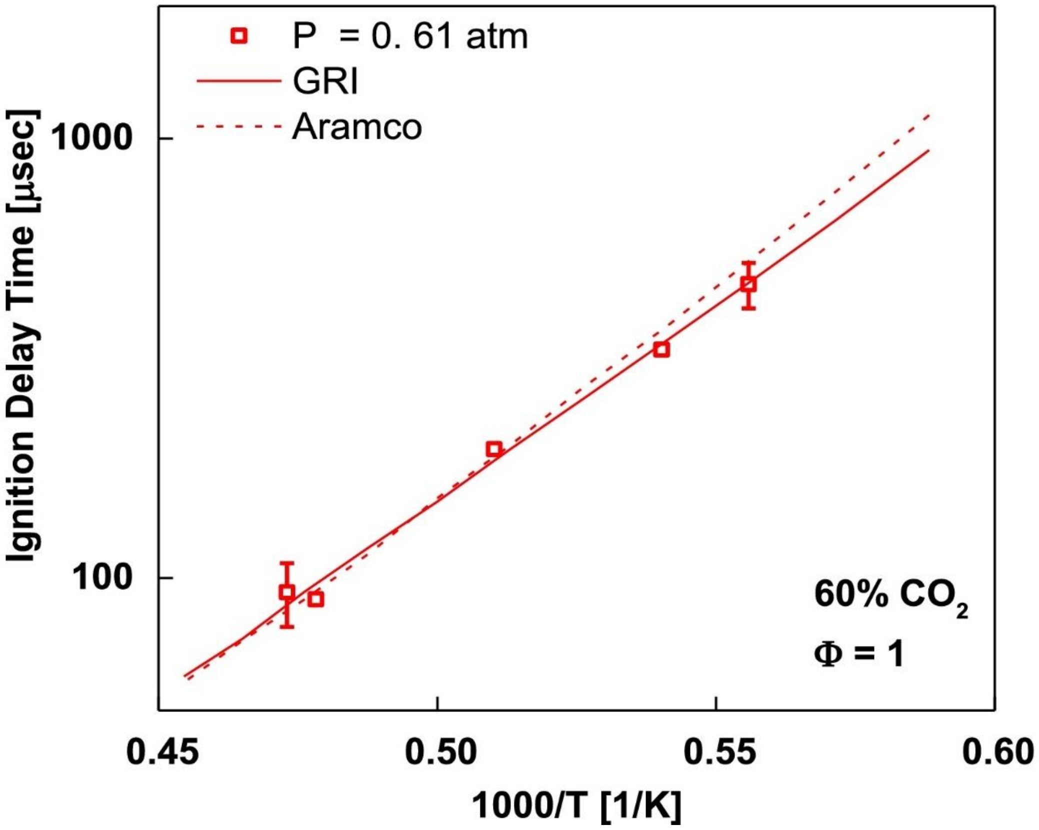
Single vs. Double-flow Turbine Layout

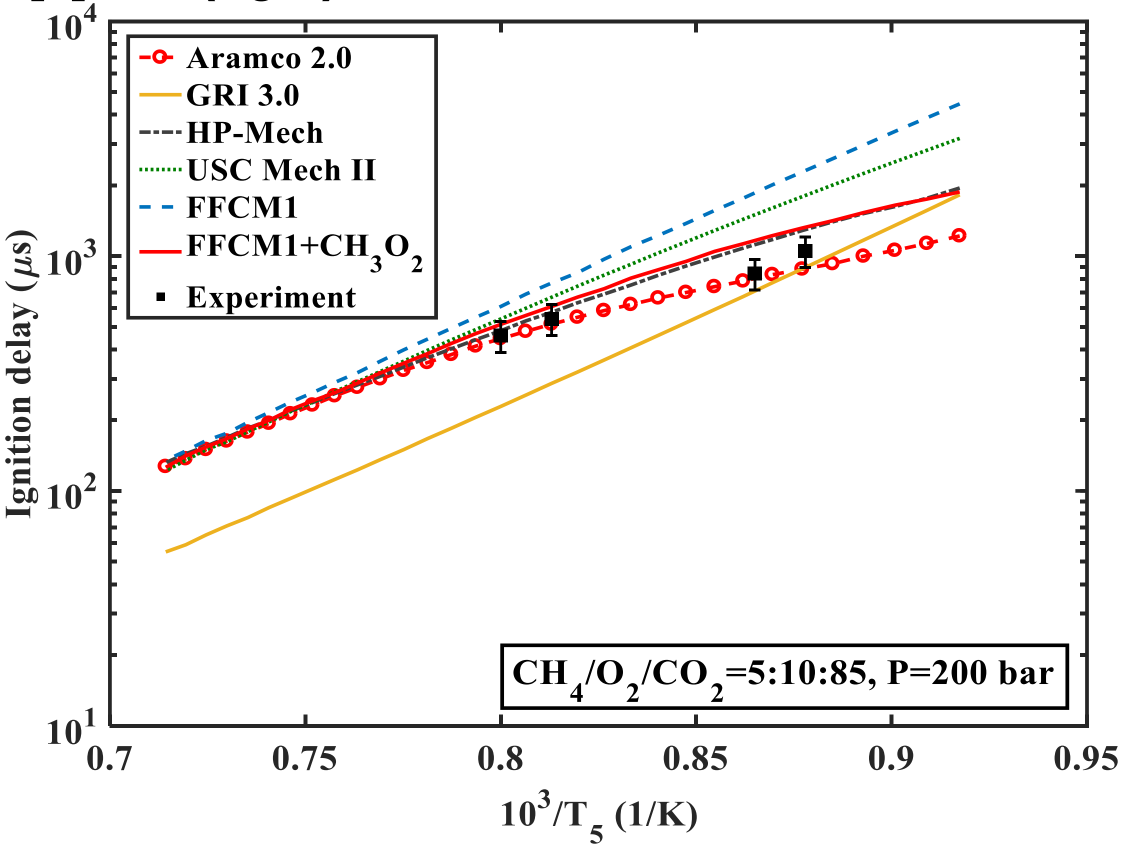
- Optimum number of stages selected for each configuration
- Includes effects of shaft seals
- Single flow has better aero efficiency and lower seal leakage
  - Less leakage for seals that inject cooling flow into rotor
- 5 stage single flow design showed optimum performance

FLAVOR	STAGES	COOLING	SEAL LEAKAGE	TOTAL	AERO	RELATIVE EFFICIENCY CHANGE
	#	% of Recycle Flow			%	%
SINGLE	4	4.16	3.40	7.56	88.3	1.19
SINGLE	5	5.55	3.40	8.95	90.0	1.92
SINGLE	6	7.47	3.40	10.87	91.1	1.69
SINGLE	8	11.20	3.40	14.60	92.0	0.00
SINGLE	10	15.86	3.40	19.26	92.1	-3.13
DOUBLE	8	8.00	7.50	14.30	89.8	-1.99

Combustion Kinetics Evaluation

Ignition delay time measurements of stoichiometric $CH_4/O_2/CO_2$ mixtures at (left) 0.61 atm [1] and (right) 200 bar



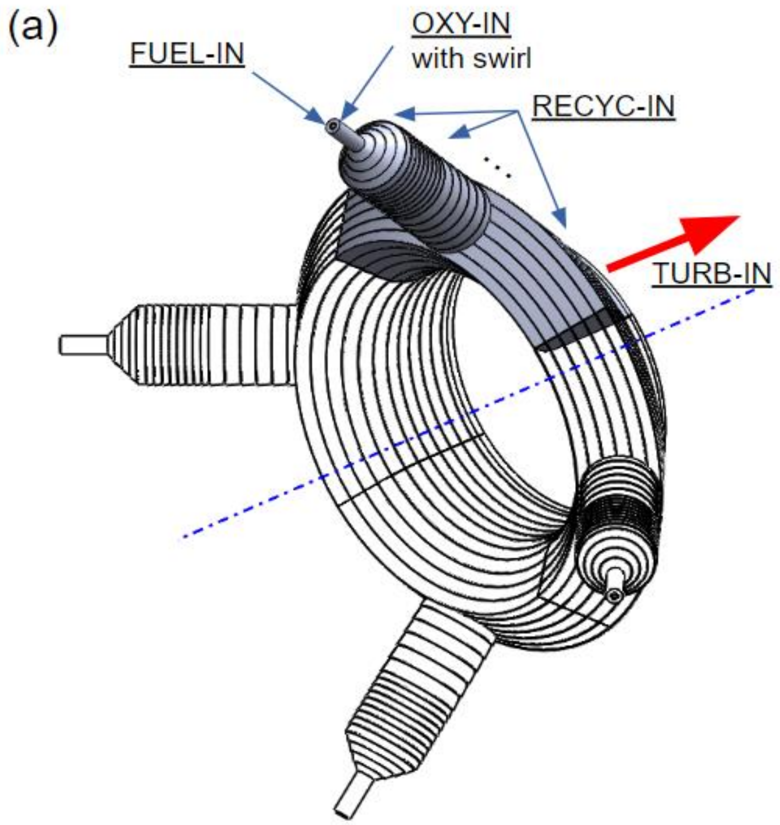


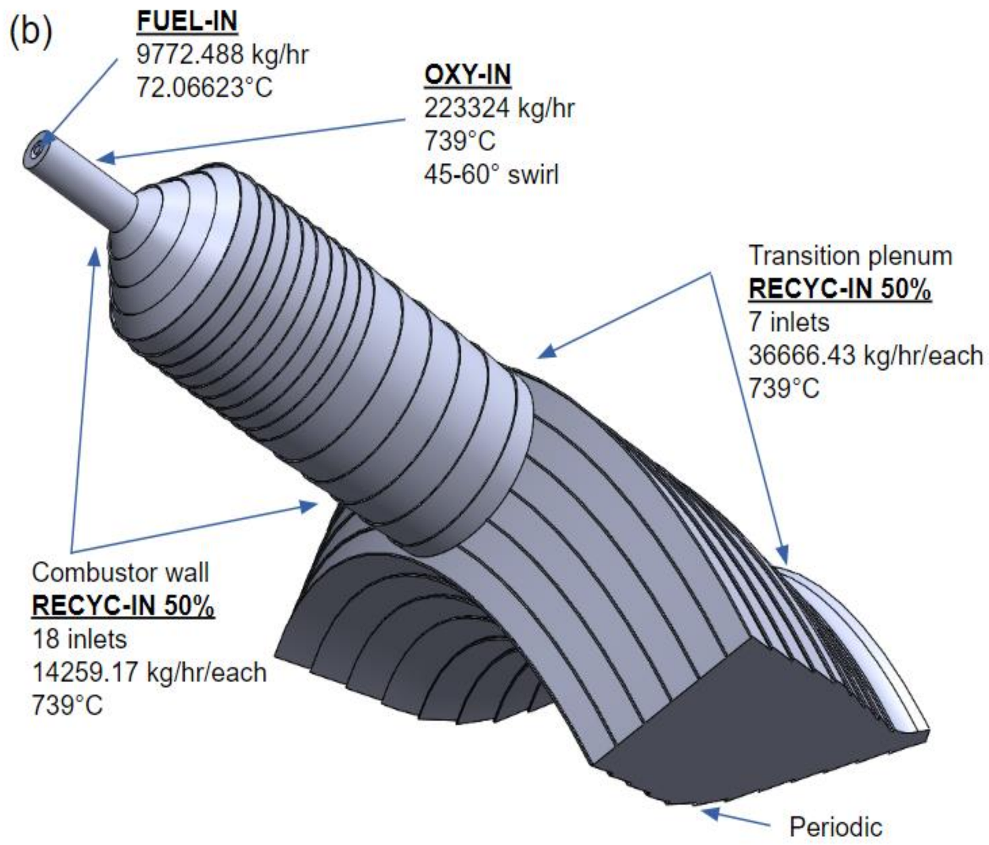
At 200 bar significant deviation between experiments and prediction from GRI Mech 3.0

B. Koroglu, et al., Combust. Flame, 2016

Oxy-Fuel Combustor Concept

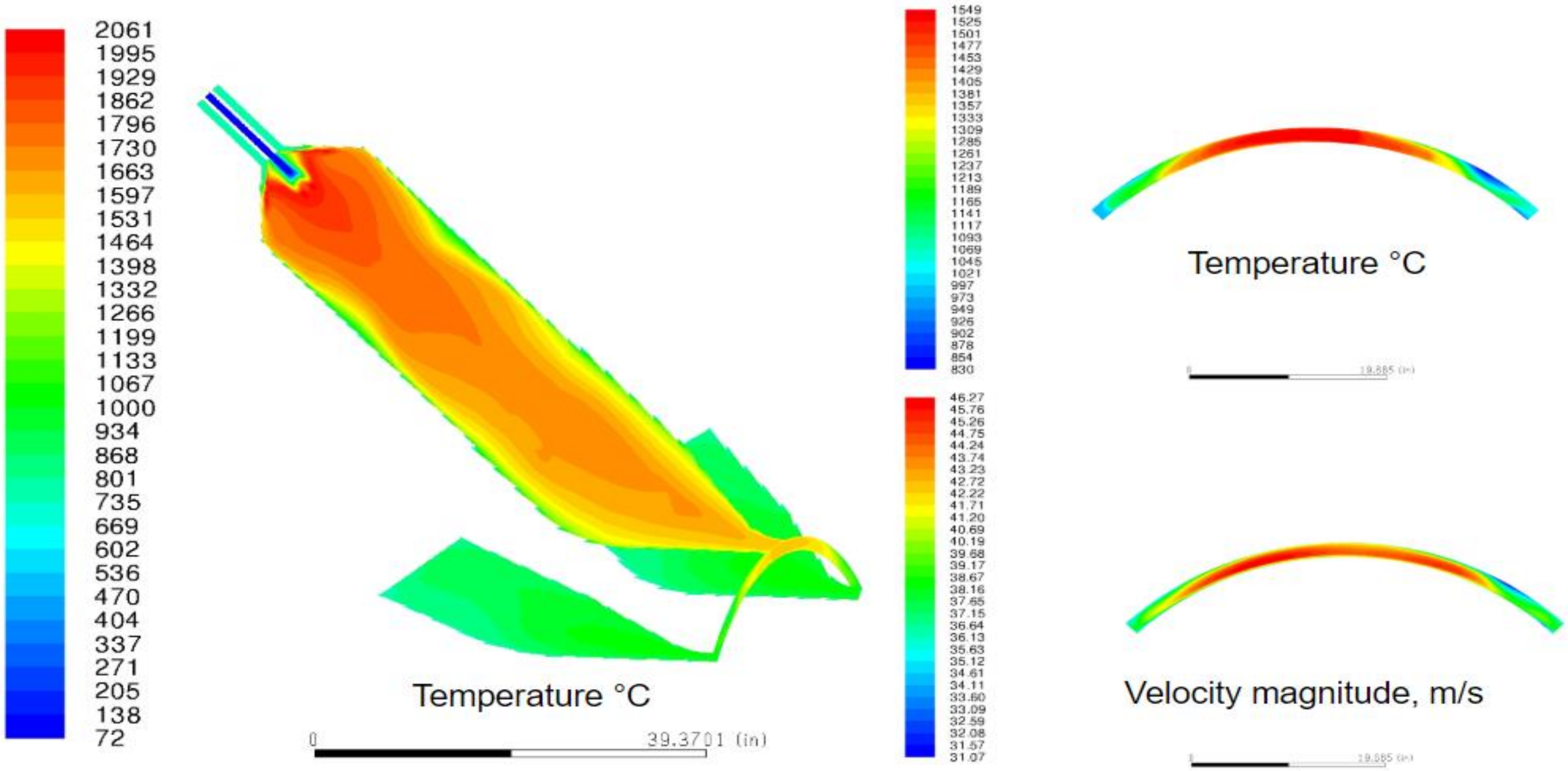
ISO view of conceptual combustor geometry for straight through turbine design with 4 combustor cans, and 3D CFD fluid volume and boundary conditions

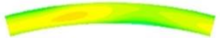


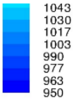


Oxy-Fuel Combustor Concept

- **3D CFD results (case 303): Temperature profile in degree C, and Velocity magnitude [m/s]**
- **Excessive temperature and velocity variation at nozzle entrance**

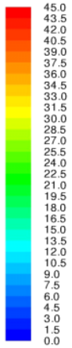
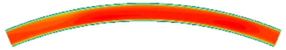
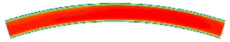
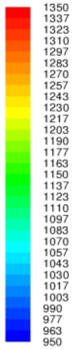
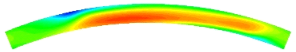
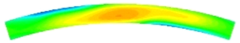
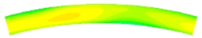


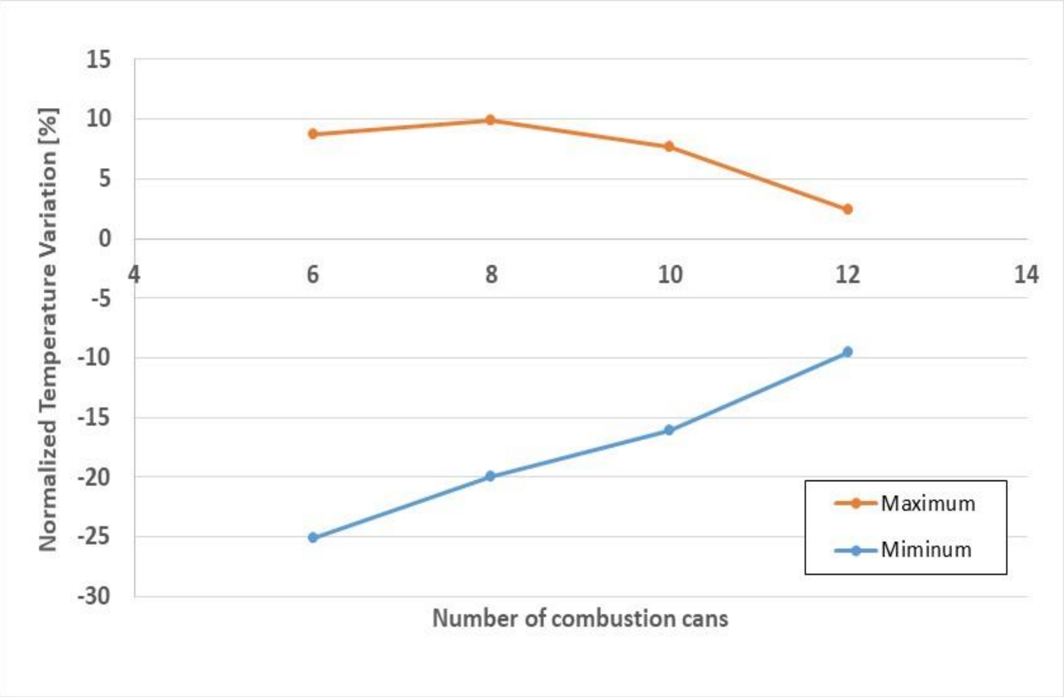




Oxy-Fuel Combustor Concept

Summary of 3D CFD results at the transition plenum exit: Velocity magnitude and Temperature profile

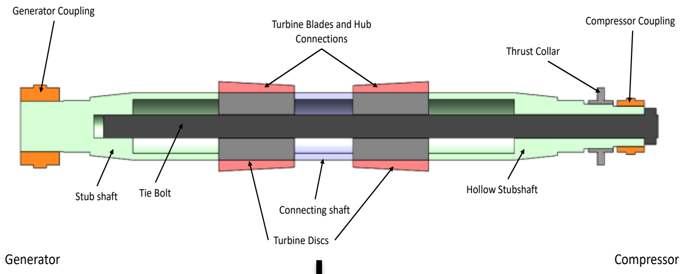
		8 combustion cans	10 combustion cans	12 combustion cans
Velocity [m/s] profile				
Temperature [°C] profile				

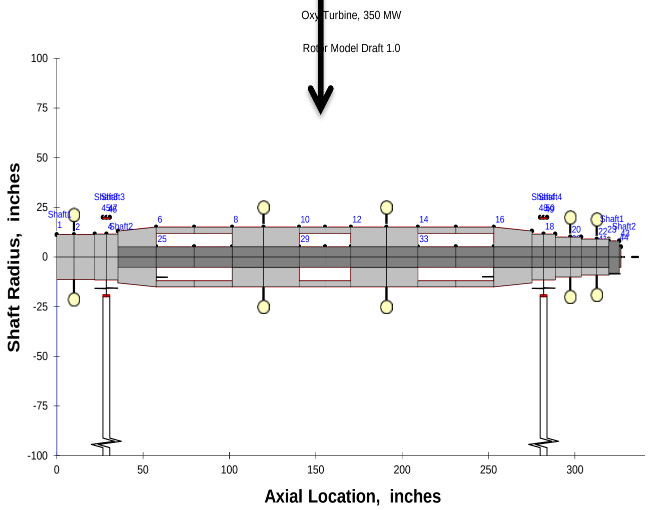


Rotordynamic Modeling

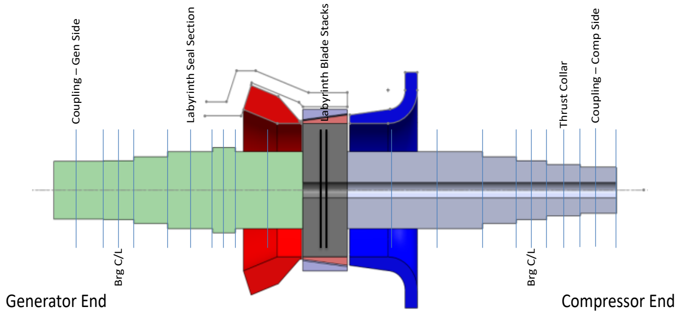
Comparison of Back-to-Back and Inline Turbine Design

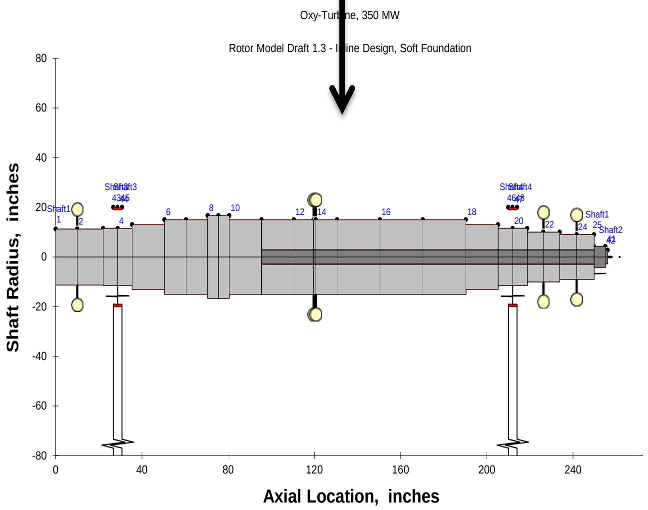
Back-to-back turbine design





Inline turbine design

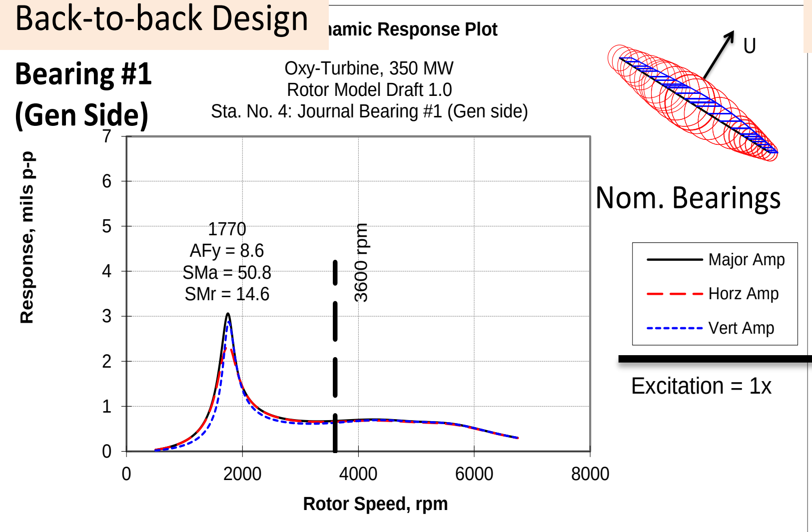




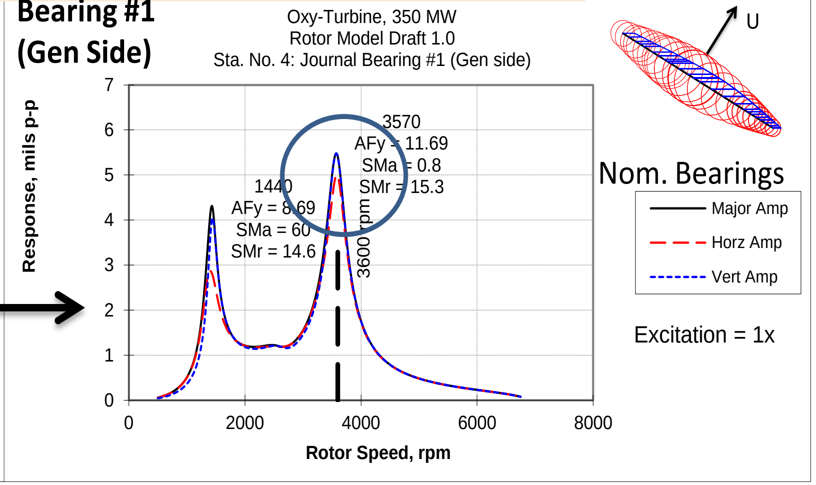
Rotordynamic Modeling

Unbalance Response

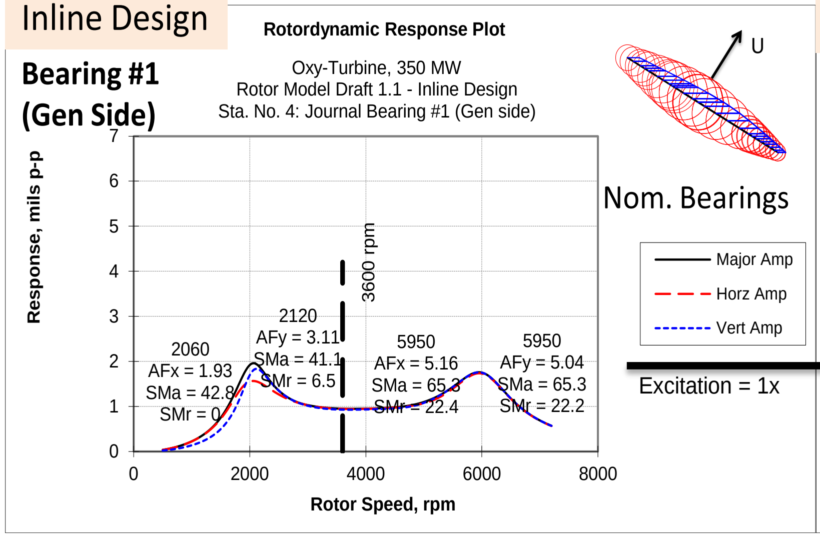
Back-to-back Design



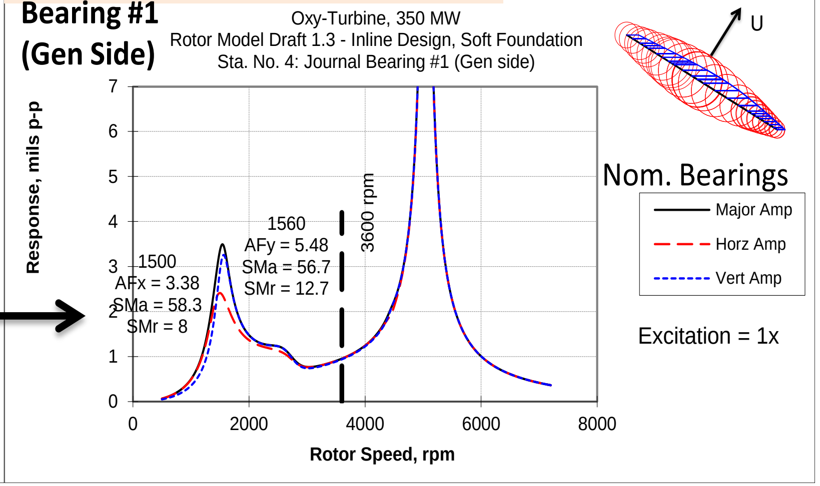
Back-to-back Design, Soft Foundation



Inline Design



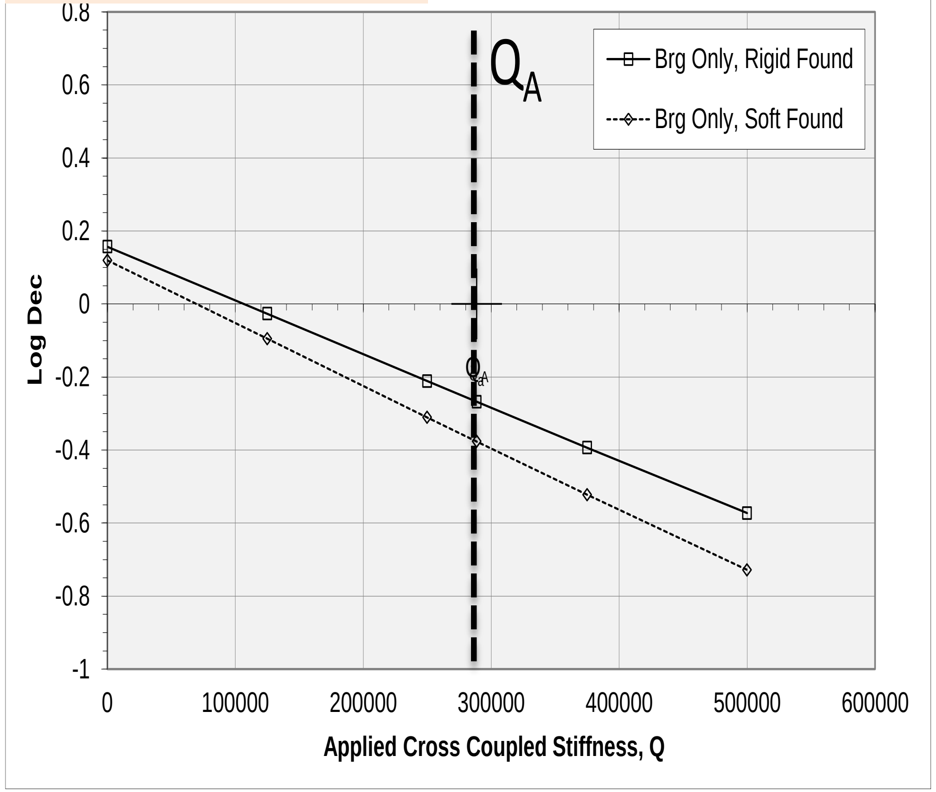
Inline Design, Soft Foundation



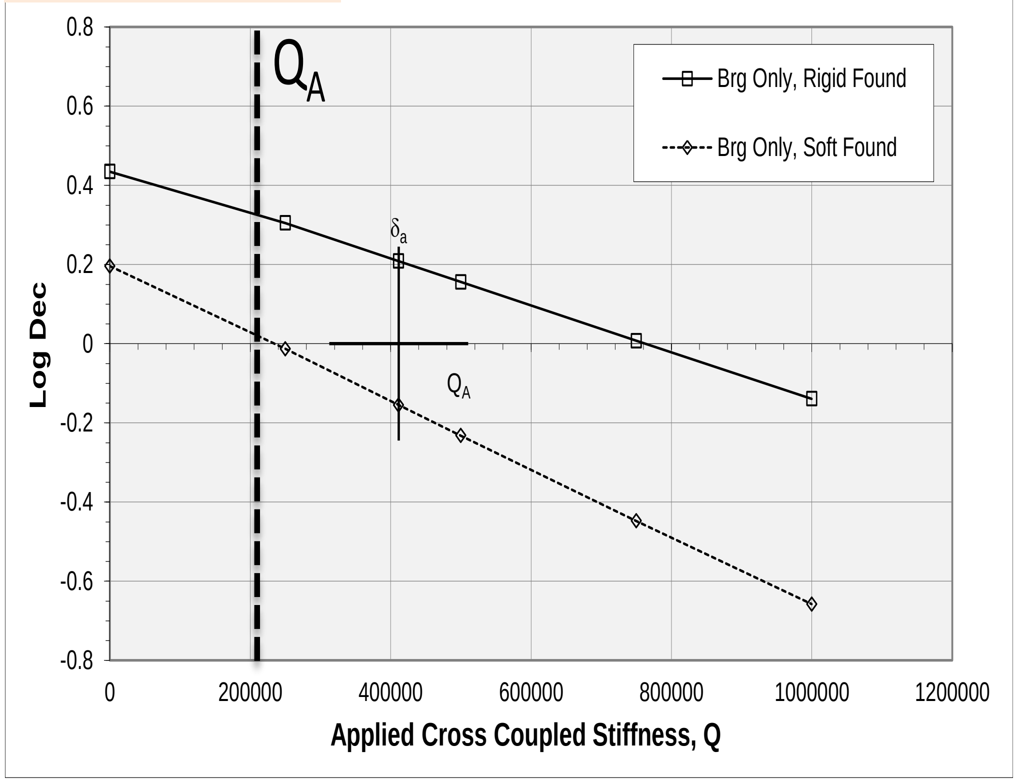
Rotordynamic Modeling

Stability Analysis

Back-to-back Design



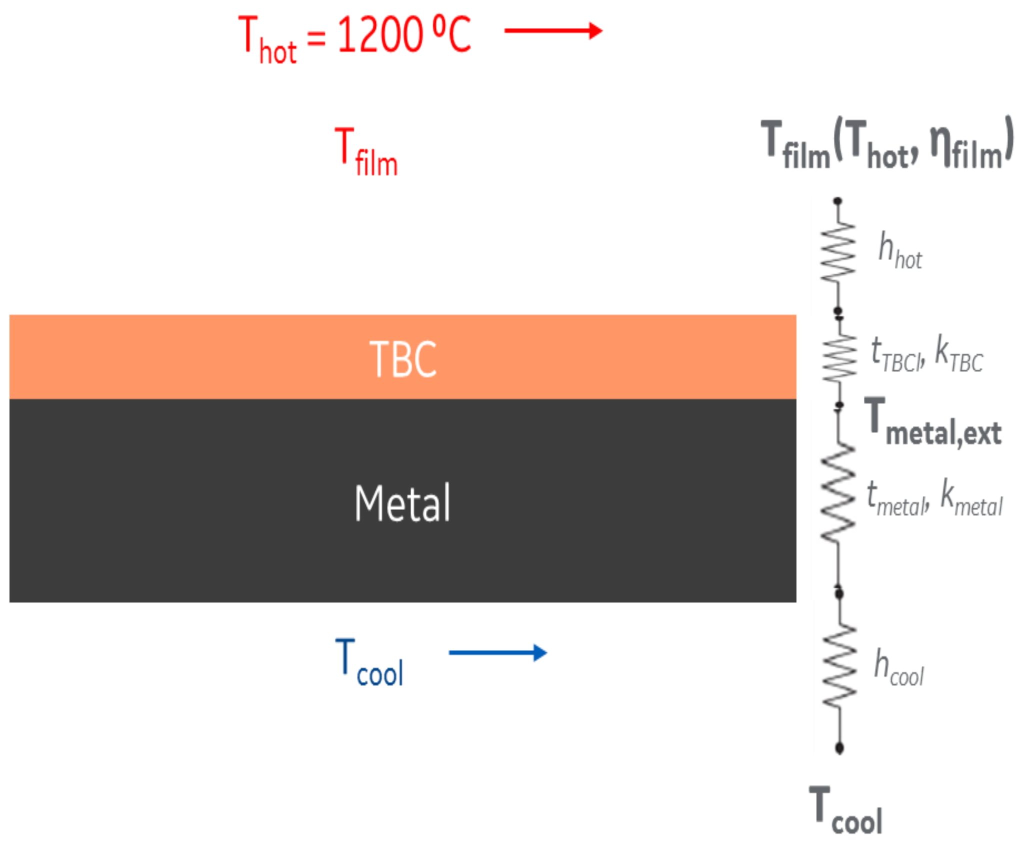
Inline Design



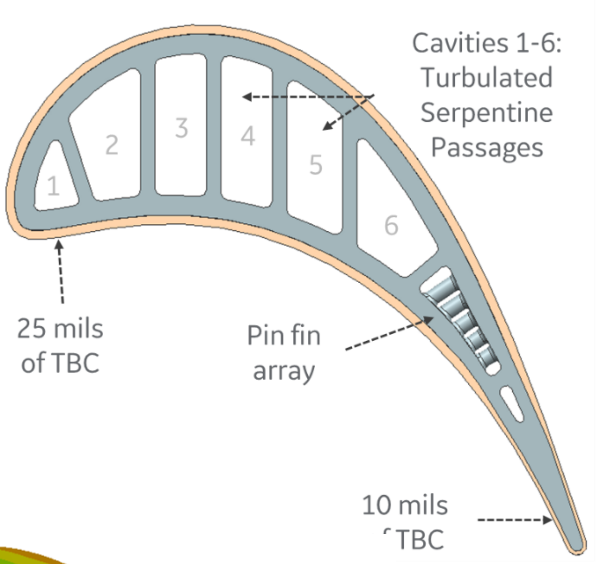
1-D Heat Transfer Analysis

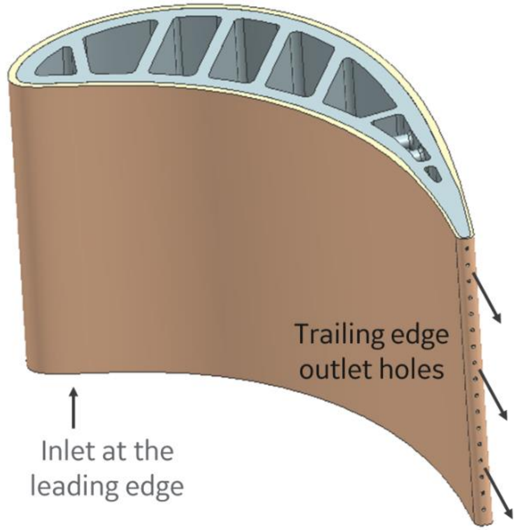
- High density of CO_2 results in high heat transfer coefficients
- Metal temperature target < 750°C
- Cooling temperature 430°C

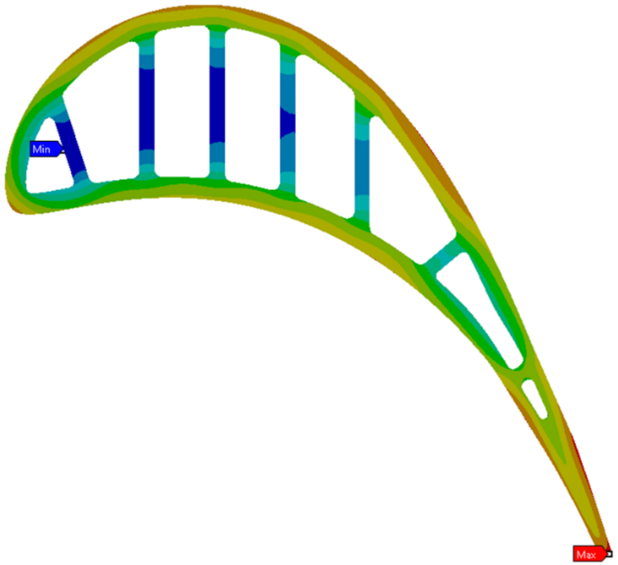
Flow path	Stages	Cooling (% of Recycle-In)
Single	4	4.2
Single	5	5.6
Single	6	7.5
Single	8	11.2
Single	10	15.9
Double	8	8.0
Double	10	9.2
Double	12	12.4

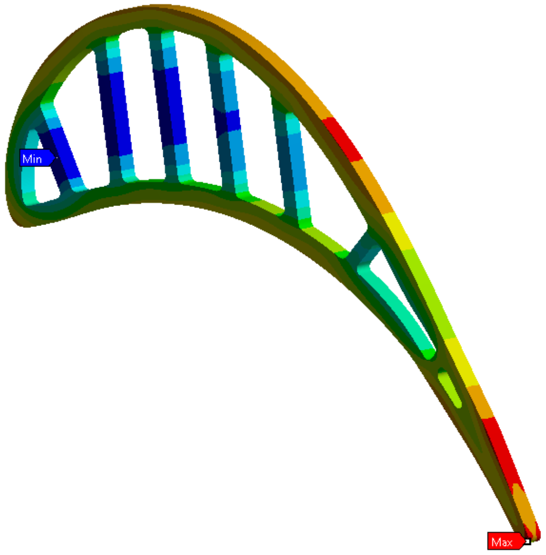


2-D Heat Transfer Analysis

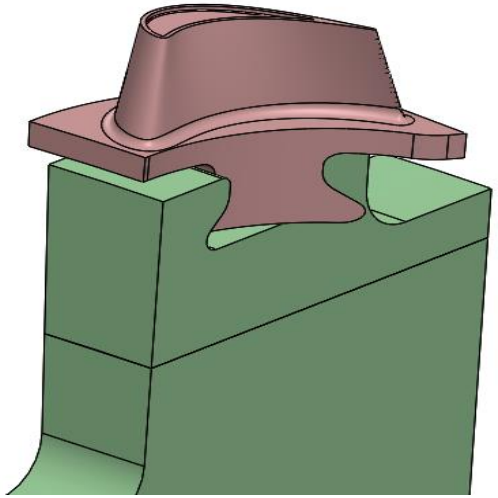


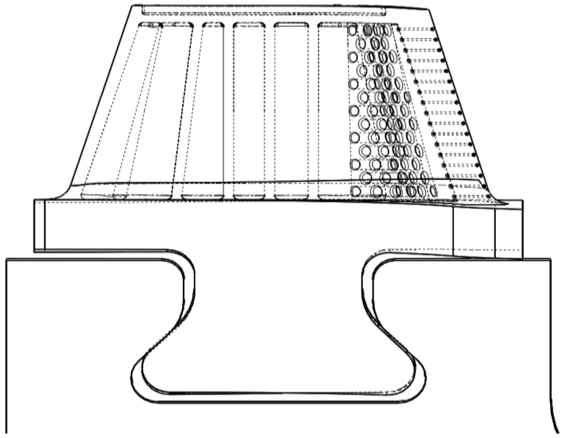


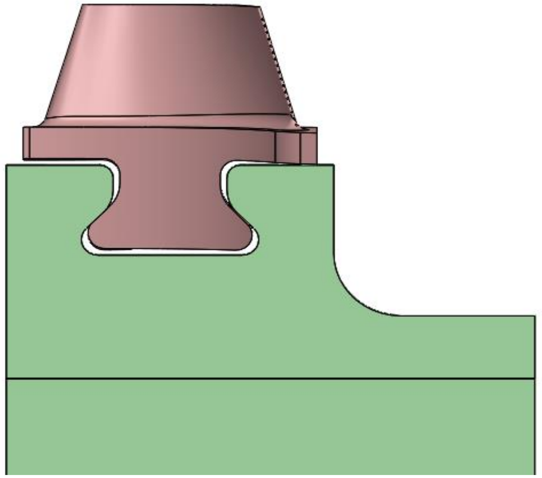




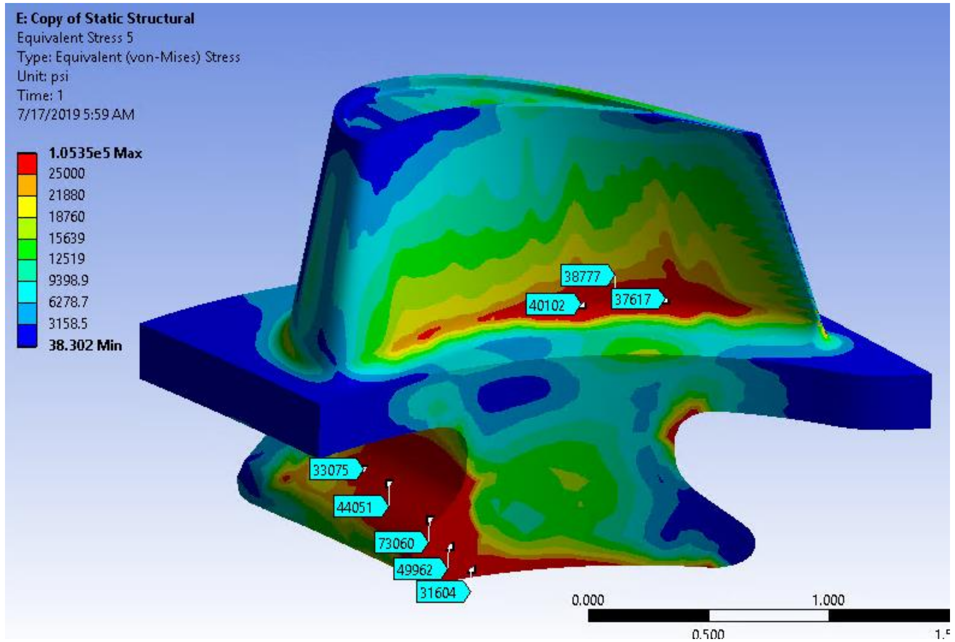
3D Blade Model

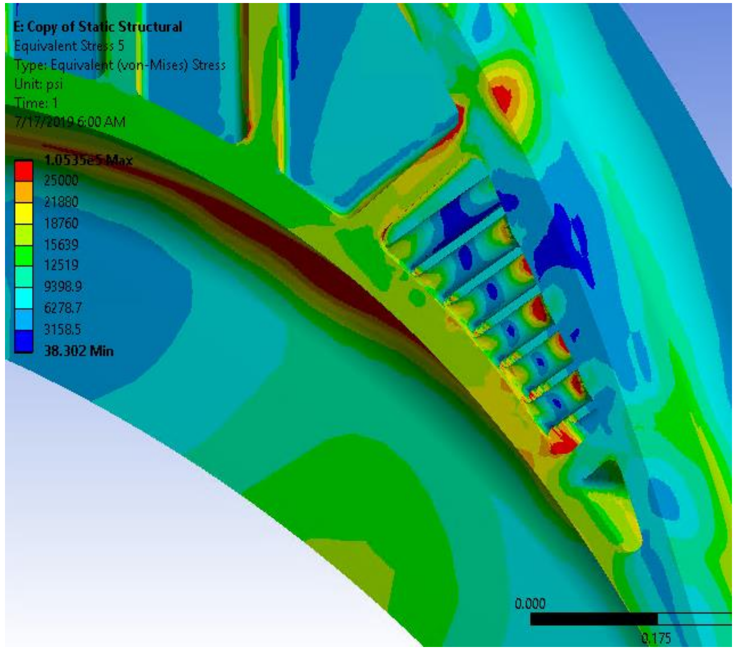






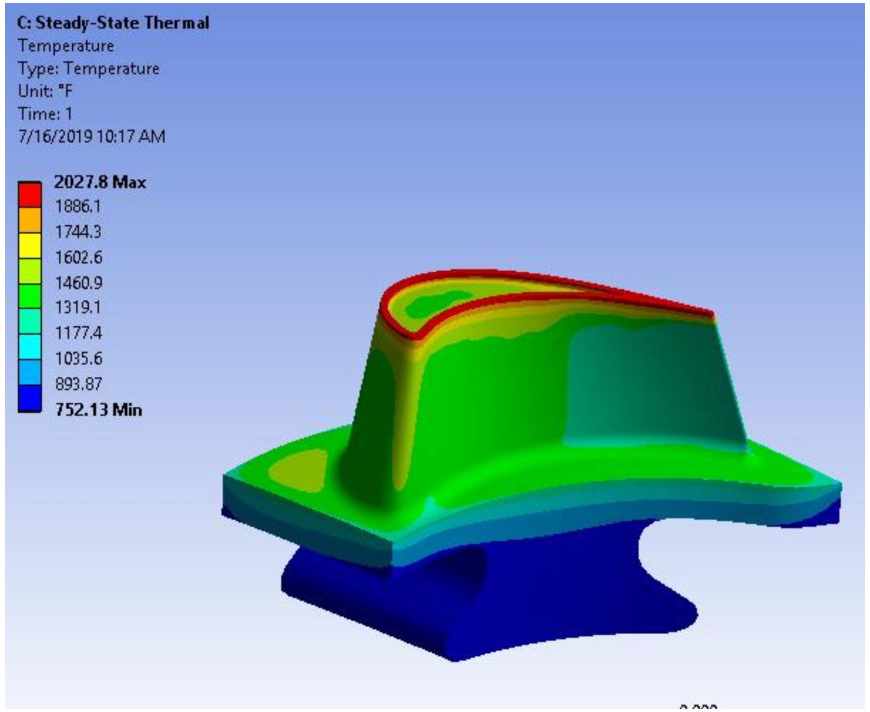
Structural Stress Results (Torque, Rotation, Pressure)

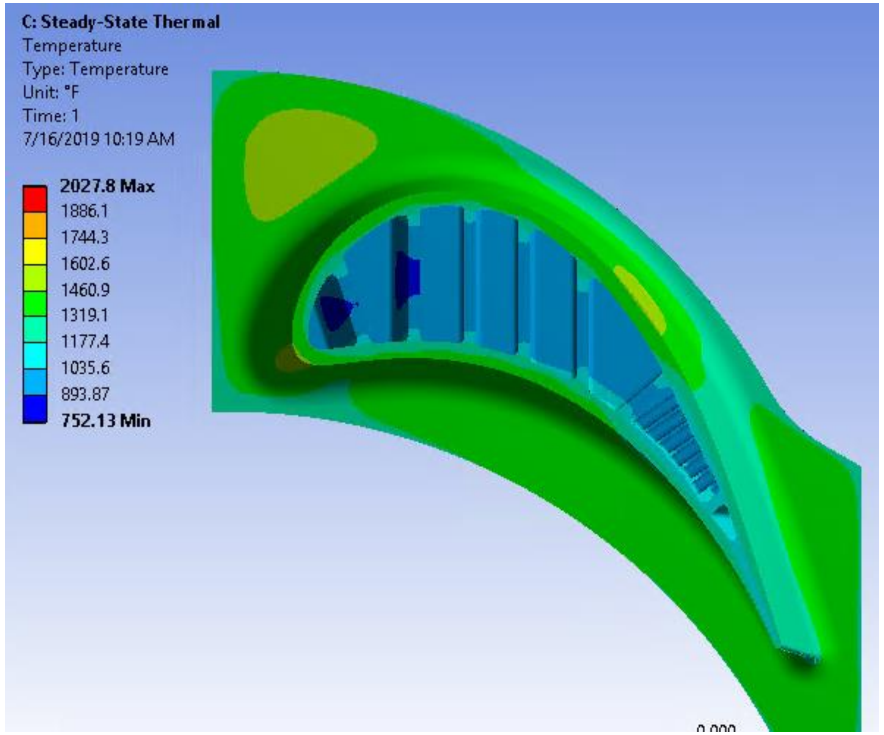




Thermal Stress Analysis

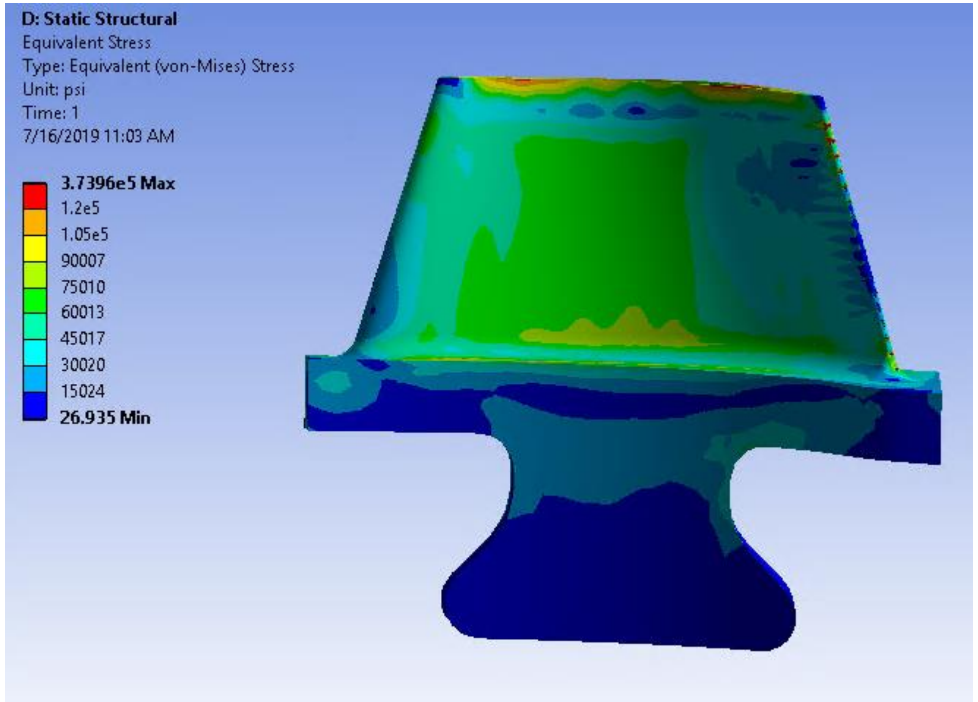
Temperature

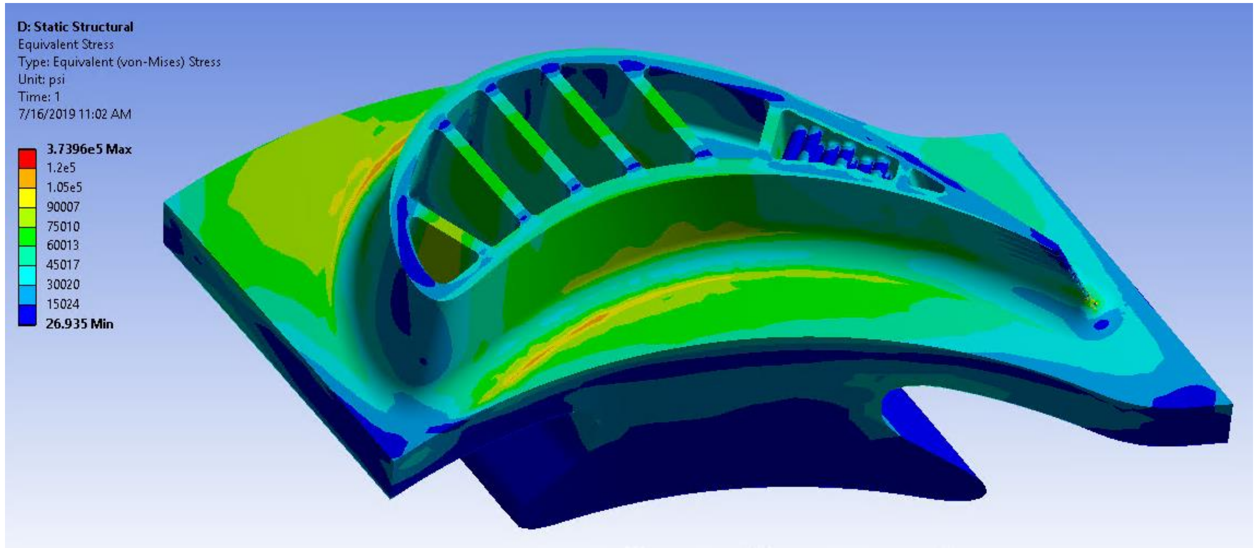




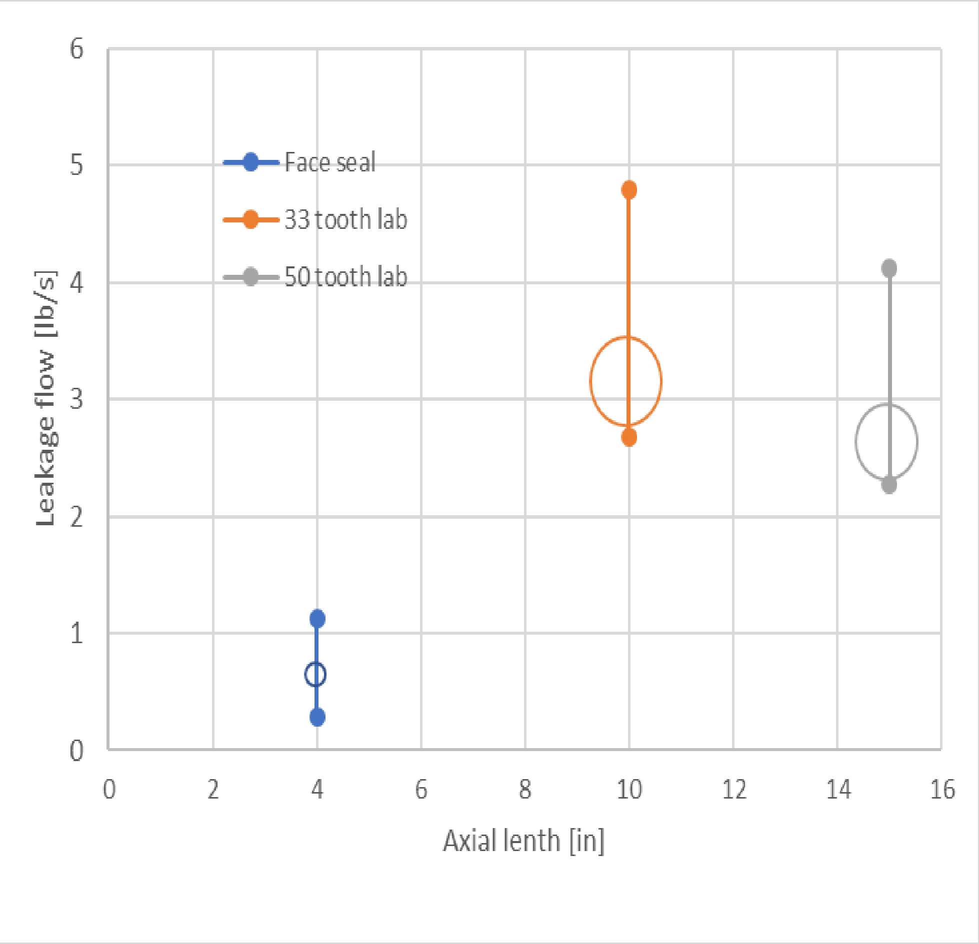
Thermal Stress Analysis

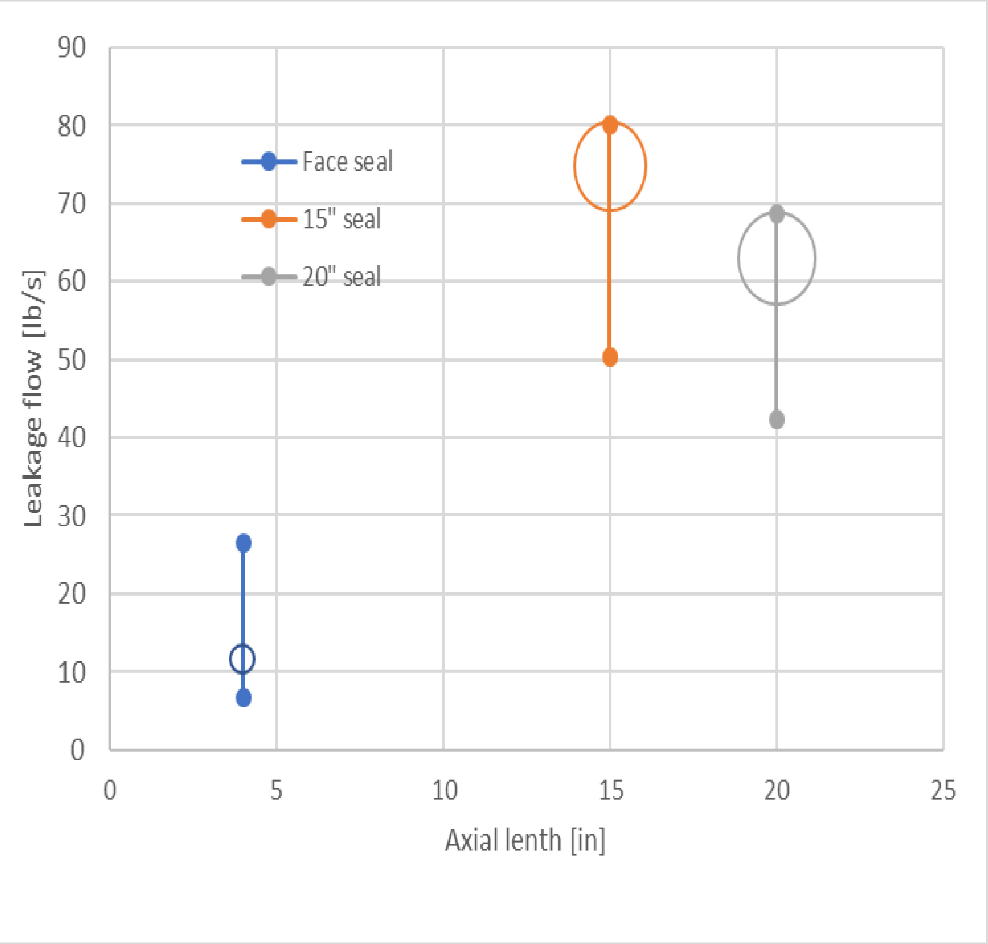
Stress Results



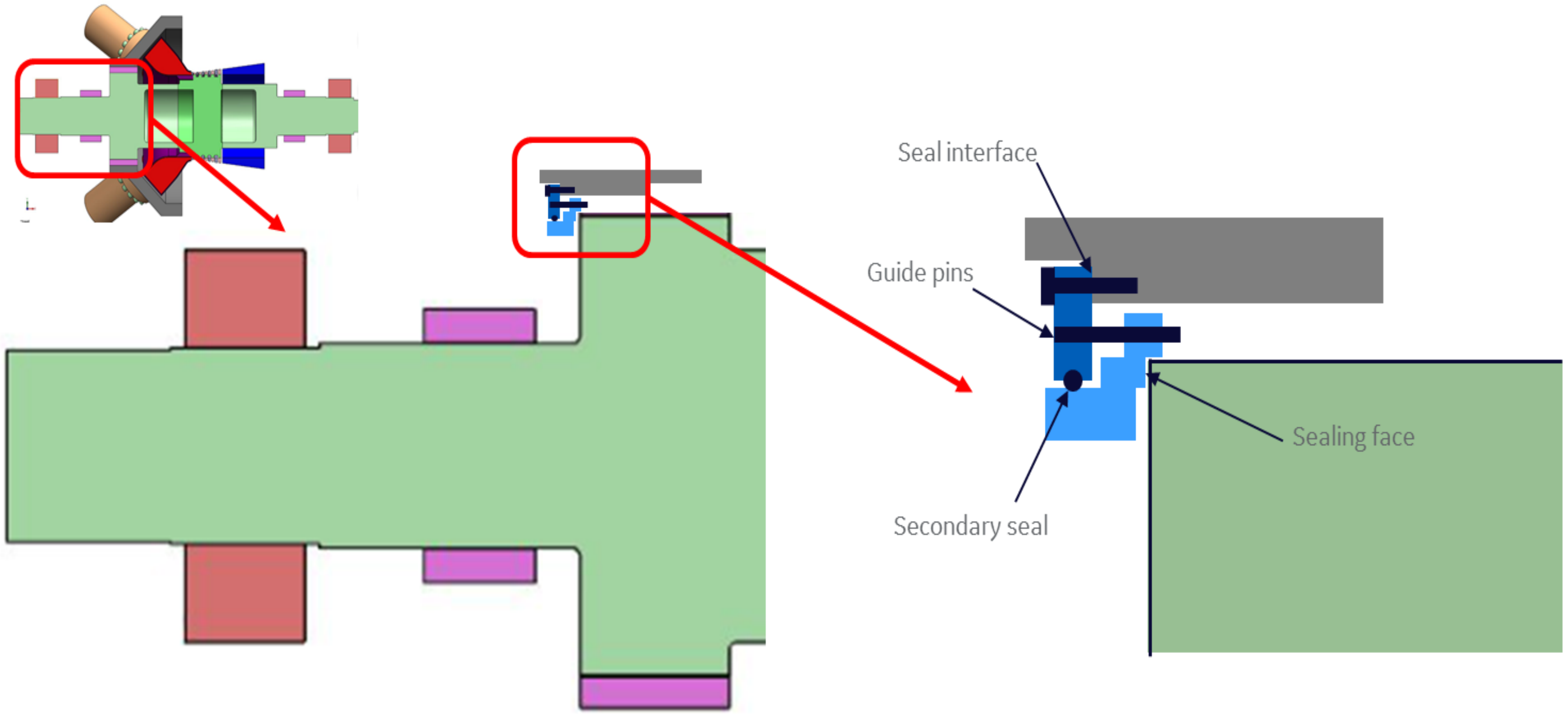


Shaft End and Balance Piston Seals





Shaft End and Balance Piston Seals



Turbine Conceptual Layout

Key information needed to start the case layout:

•Inlet and Exhaust Flow Conditions

- -Temperature – Necessary materials and boundaries
- -Pressure – Wall thicknesses and case configuration
- -Volume Flow – Required flow area to keep velocities relatively low (<30 m/s)

•Aerodynamic Flowpath

- -Hub Diameter – Maximum diameter of the main shaft
- -Number of Stages – Required axial length for the turbine blades
- -Configuration – Overhung, straddle, straight through, back-to-back

•Combustor Can Geometry

- -Number of Cans – Radial spacing and organization around the case
- -Can Diameter – Required penetrations and connections to the case

Operating Conditions

Below are some of the key operating conditions that affect the overall design of the turbine:

	Inlet	Exhaust	Recycle	Cooling
Temperature [C]	1,200.0	778.4	739.0	430
Pressure [bar]	305.0	30.0	315.0	316.5
Flow [m^3/hr]	30,544	223,808	13,745	1,043.8

Turbine Conceptual Layout

Rotor layout options

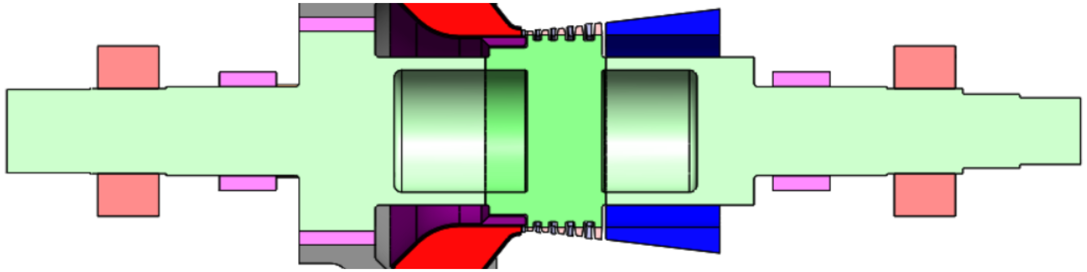
5-Stage Straight Through

- Fewer blades, shorter span, larger hub diameter
- While this is not advantageous for a case design, a larger hub diameter does lead to better rotordynamic stability
- Balance piston required but can be a source of damping

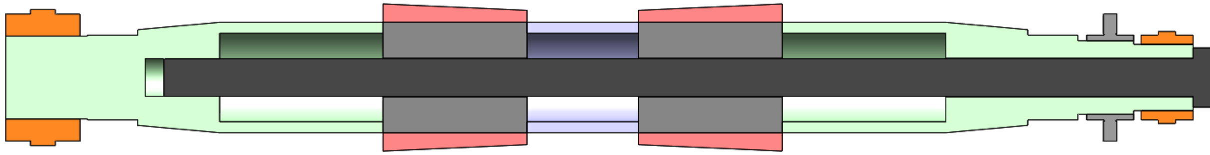
12-Stage Back-to-Back

- Smaller hub diameter which leads to thinner casings and lower stresses on the turbine blades
- Due to the back-to-back design, the pressure is balanced and there is no need for a balance piston to balance the thrust
- Rotor cooling seals required on both ends create more leakage than straight through design

5-Stage Straight Through Rotor Layout



12-Stage Back-to-Back Rotor Layout



Turbine Conceptual Layout

1 – Main Cooling Supply to Turbine Case and Rotor

2 – Main Cooling Supply to Stators and Blade Shrouds

3 – Remaining Cooling Flow that Cools Recycle Flow Liner

4 – Balance Piston Flow

4a – Case cooling Flow

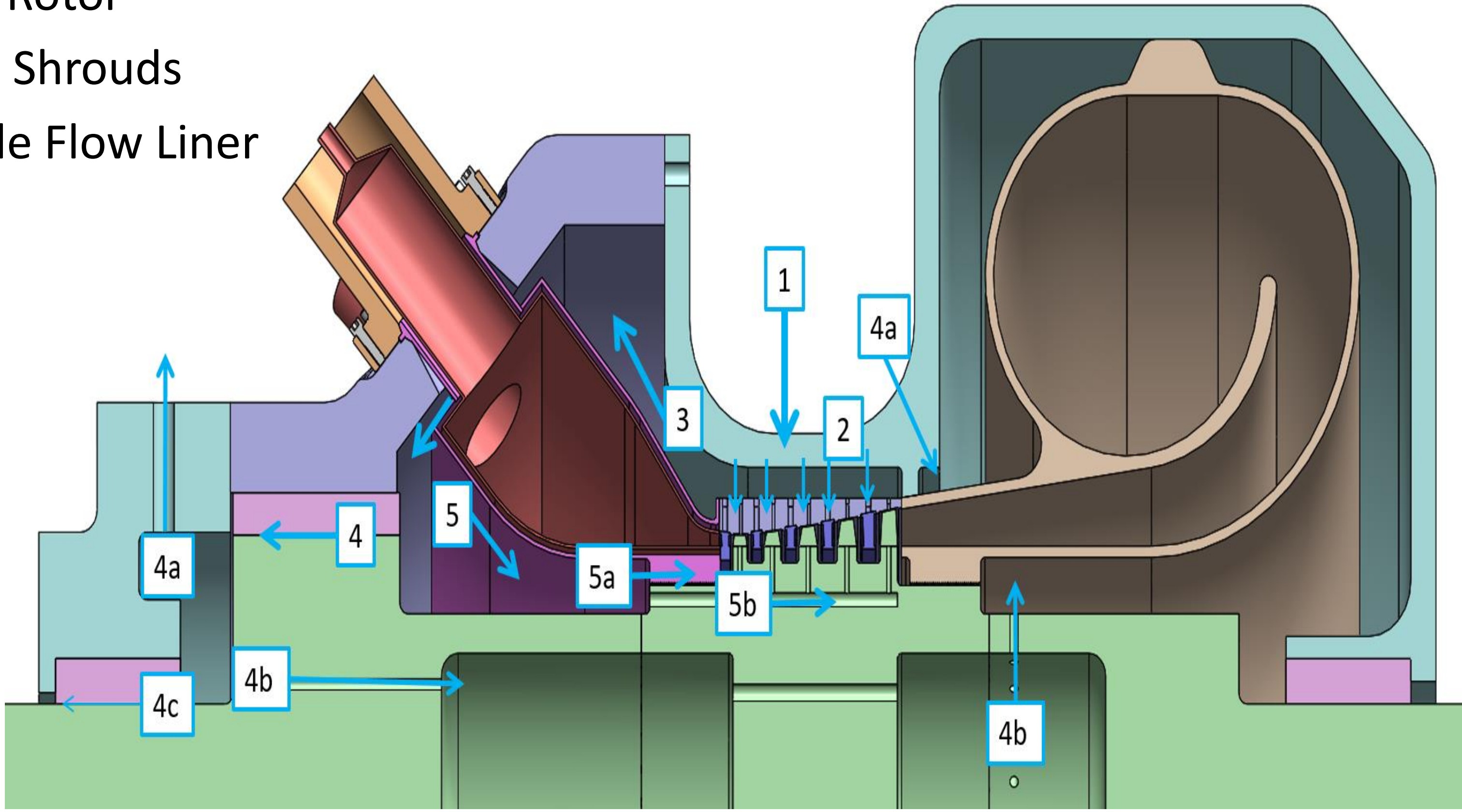
4b – Rotor and Case Cooling Flow

4c – End Seal Leakage

5 – Cooling Flow to Buffer Recycle Flow Liner

5a – Stage 1 Buffer Flow

5b – Blade Cooling Flow



Summary and Project Goals

- Achieved greater than 58% thermal efficiency in the cycle analysis
- Developed aerodynamic design for first stage nozzle and turbine blade with efficiency greater than 85%
- Developed cooled nozzle and turbine blade design with metal temperature in high-stress areas less than 700°C.
- Developed a conceptual design for the oxy-fuel combustor to achieve a firing temperature of 1,200°C
- A conceptual layout completed including cooling scheme, seal layout, and rotordynamic evaluation
- Further development testing needed in kW and MW scale combustion testing
- Further development testing needed in blade cooling heat transfer coefficients
- Further development testing needed in material and TBC testing at 1200C in CO_2
- Phase 2 will complete detailed turbine design