Practical Considerations for the Conceptual Design of an sCO2 Cycle

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Agenda

- Conceptual Design Process
- Cycle Design Considerations
- Machinery Design Considerations
- Case Study

System and Component Design Process

Step One: Pick your application

Primary Power

- High grade heat
- Optimized for system efficiency

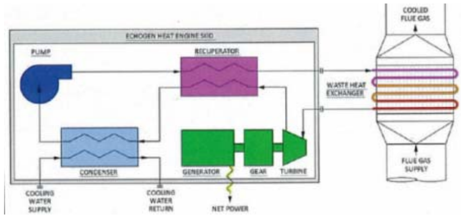
Concentrating Solar Power

Fossil Fuel

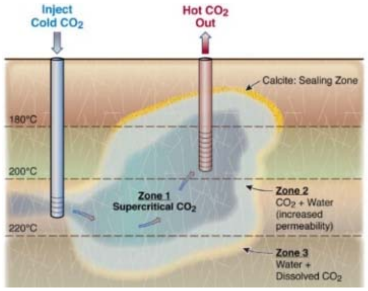
Nuclear

Bottoming Cycles

- Low grade heat
- Optimized for net power



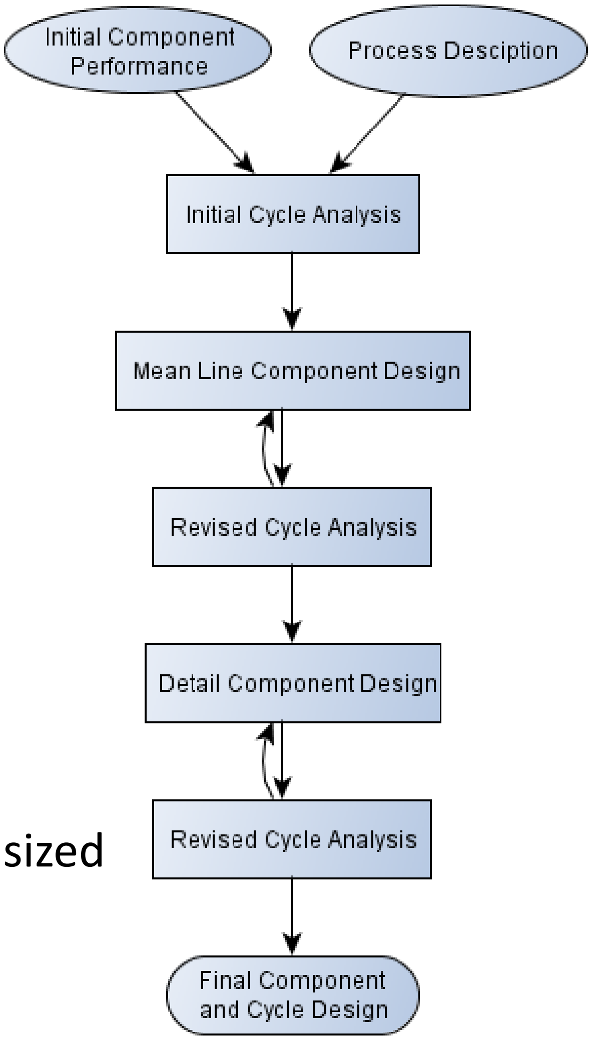
Waste Heat Recovery



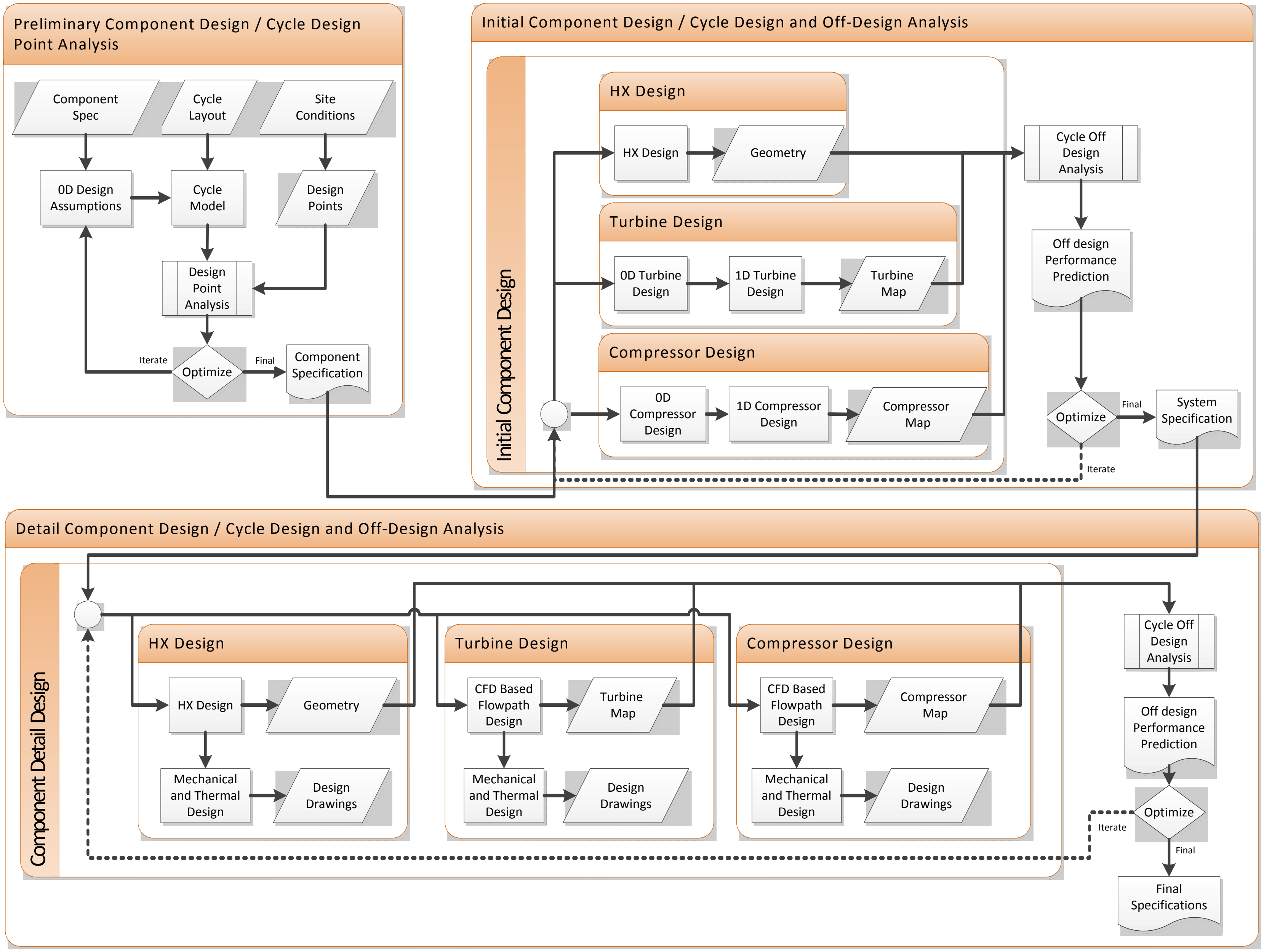
Geothermal

Step Two: System Definition and Conceptual Design

- Application Requirements
  - Design parameters
  - Objective functions
- Preliminary Cycle Design
  - Assumed component performance
  - Calculate component state points
  - Sweep assumptions to understand system trades
- Preliminary Component Design
  - Initial sizing using 0D and 1D analysis
  - Generate component maps and geometry
  - Refine the system losses
- System Layout
  - Select viable configuration based on machinery limitations
  - Update system performance estimates based on sized components
- Move on to Detail Design



System Design Process Flow Diagram



Preliminary Component Design / Cycle Design Point Analysis

Component Spec
Cycle Layout
Site Conditions
0D Design Assumptions
Cycle Model
Design Points
Design Point Analysis
Optimize
Iterate
Final
Component Specification

Initial Component Design / Cycle Design and Off-Design Analysis

Initial Component Design

HX Design

HX Design
Geometry

Turbine Design

0D Turbine Design
1D Turbine Design
Turbine Map

Compressor Design

0D Compressor Design
1D Compressor Design
Compressor Map

Cycle Off Design Analysis
Off design Performance Prediction
Optimize
Final
Iterate
System Specification

Detail Component Design / Cycle Design and Off-Design Analysis

Component Detail Design

HX Design

HX Design
Geometry
Mechanical and Thermal Design
Design Drawings

Turbine Design

CFD Based Flowpath Design
Turbine Map
Mechanical and Thermal Design
Design Drawings

Compressor Design

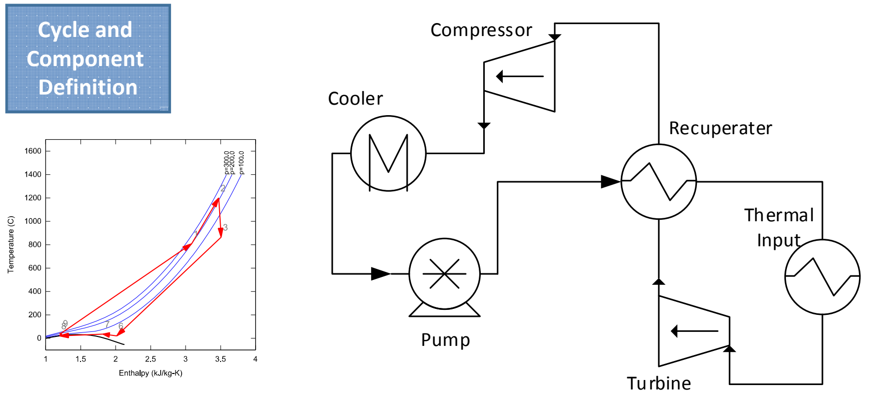
CFD Based Flowpath Design
Compressor Map
Mechanical and Thermal Design
Design Drawings

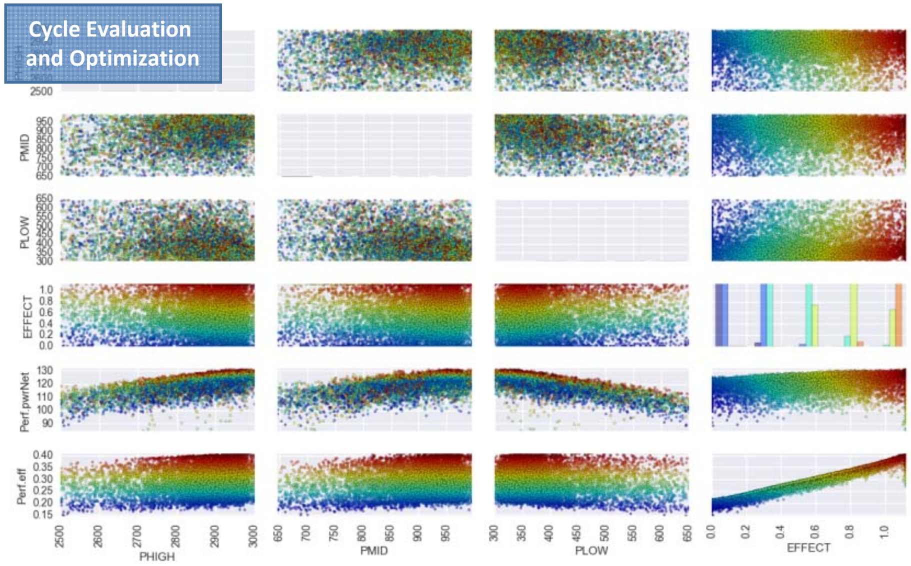
Cycle Off Design Analysis
Off design Performance Prediction
Optimize
Iterate
Final
Final Specifications

2018

System and Component Optimization

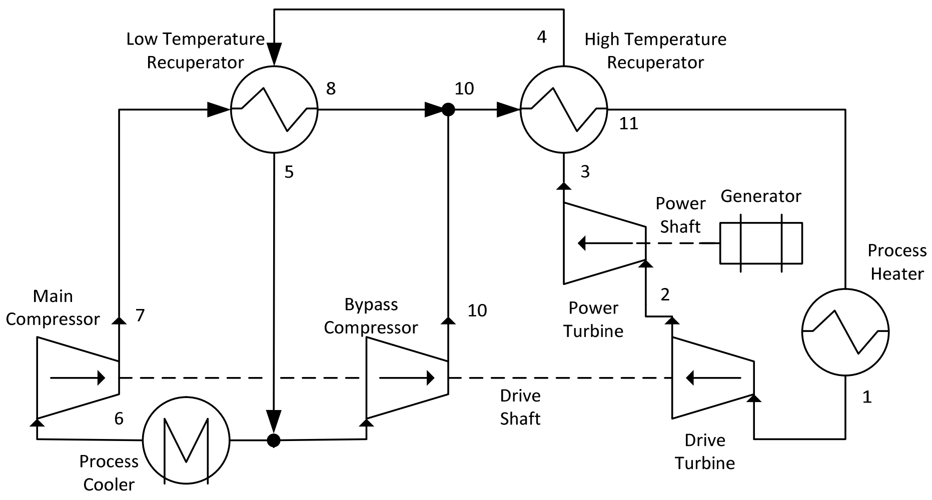
- System objectives depend on application
  - Performance
  - Cost
  - Operability
- Variety of optimization methods are available
  - Engineering judgement
  - Sweeps
  - Gradient based optimization
  - Genetic algorithms
- Advanced methods require coupling between cycles analysis and component design

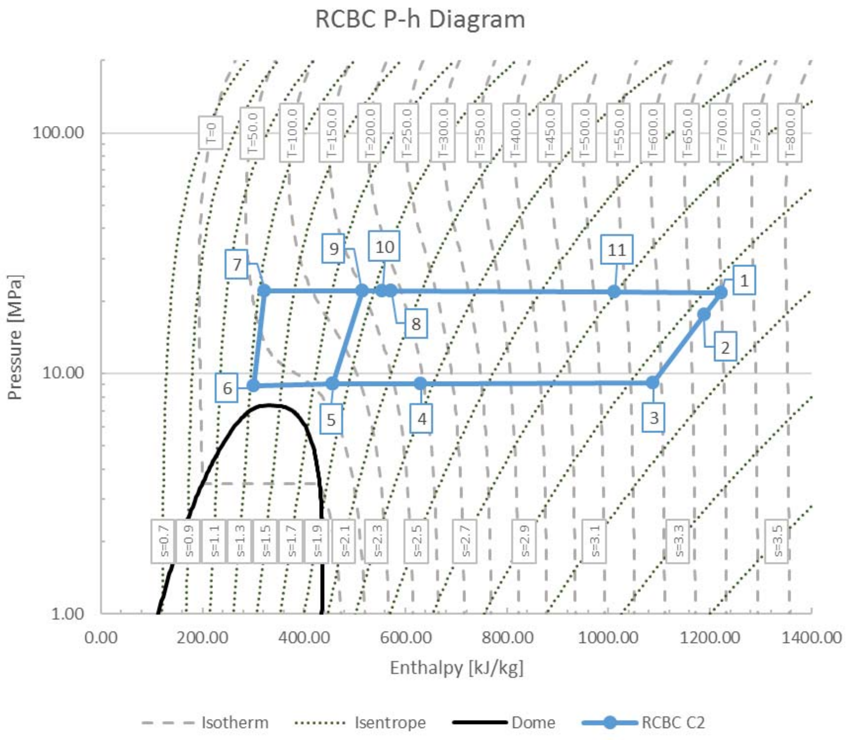

Cycle and Component Definition


Cycle Evaluation and Optimization

Cycle Design Considerations

Recompression Cycle

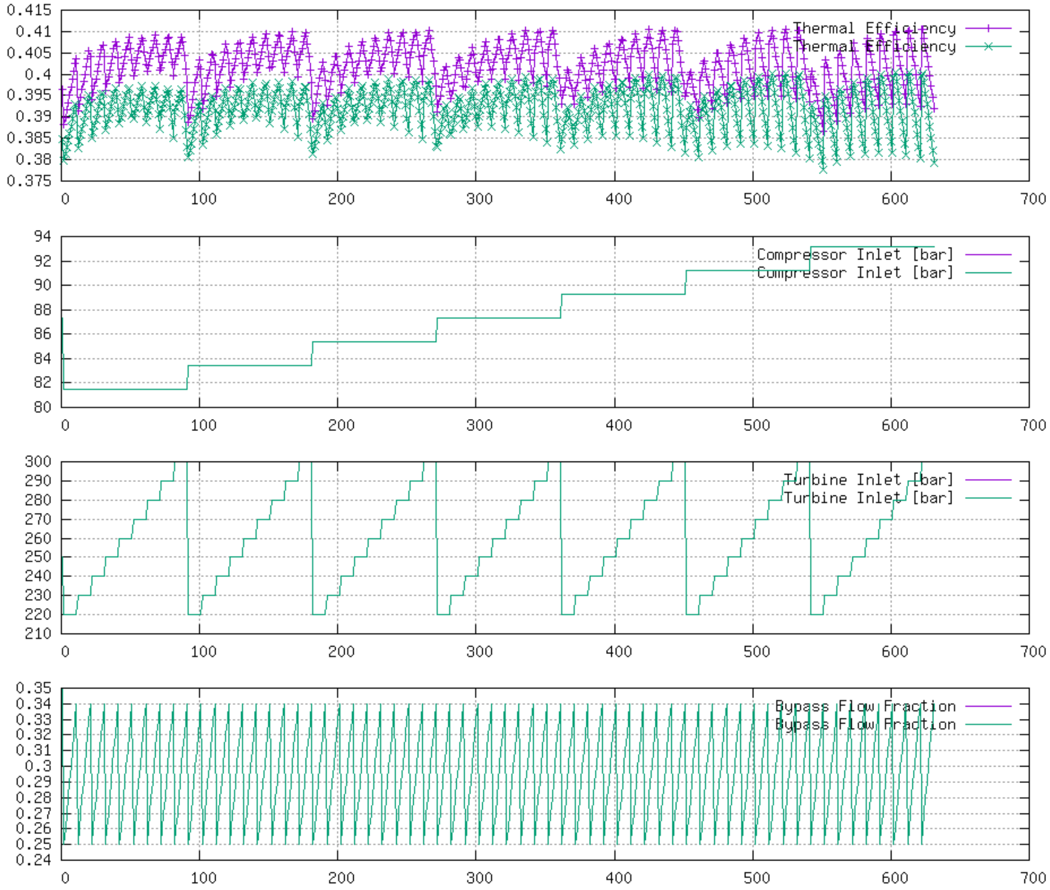




- Highly recuperated cycle achieves high thermal efficiency
- Flow split used to minimize impact of pinch point in the low temperature recuperator
- Current benchmark cycle for CSP and Nuclear applications

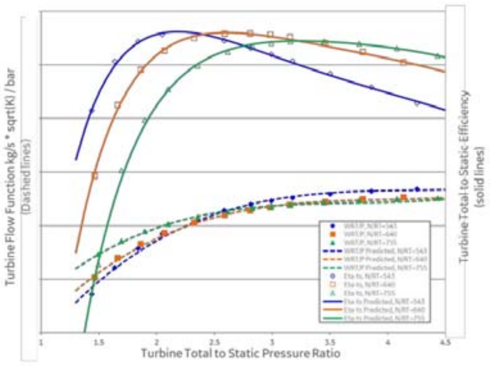
Cycle Design Point Sweep

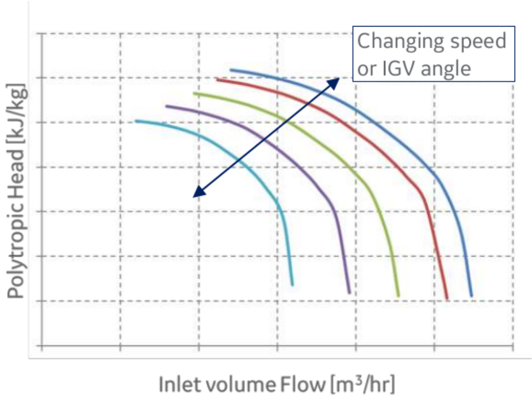
- Inputs
  - Select component operating parameters
    - Efficiency and Effectiveness
  - Sweep Design Parameters
    - Turbine Inlet Pressure
    - Compressor Inlet Pressure
    - Split Fraction
- Outputs
  - Design Objectives
    - Thermal Efficiency
    - Mass flow, specific power
  - Component state points (P,T,W) and η
    - Passed to component design

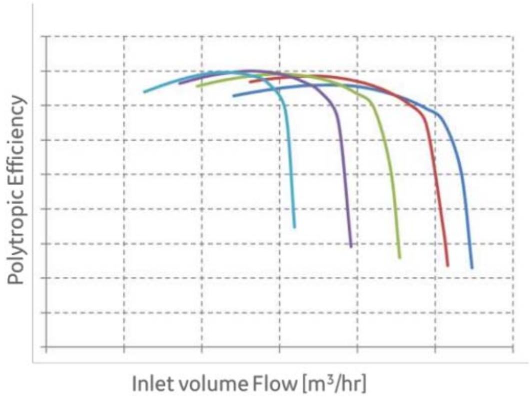


Off Design Analysis

- System off-design performance is a function of component off-design performance
    - Maps for Turbines and Compressors
    - Sized UA for Heat Exchangers
    - Finite system mass in a closed cycle

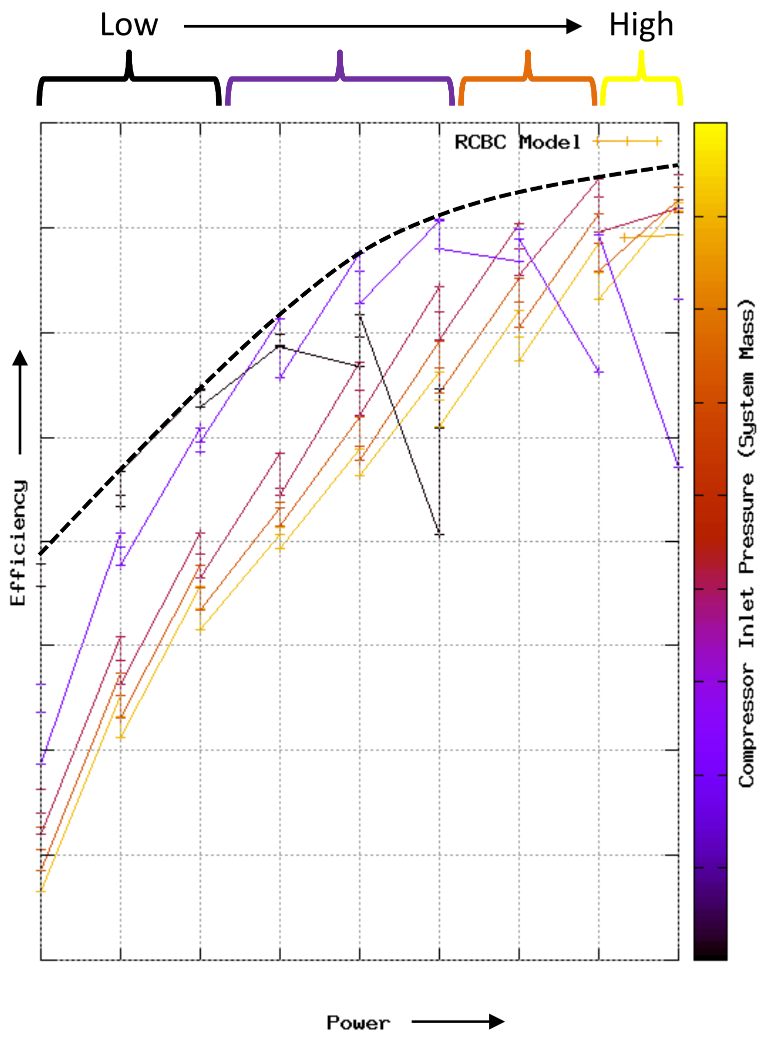






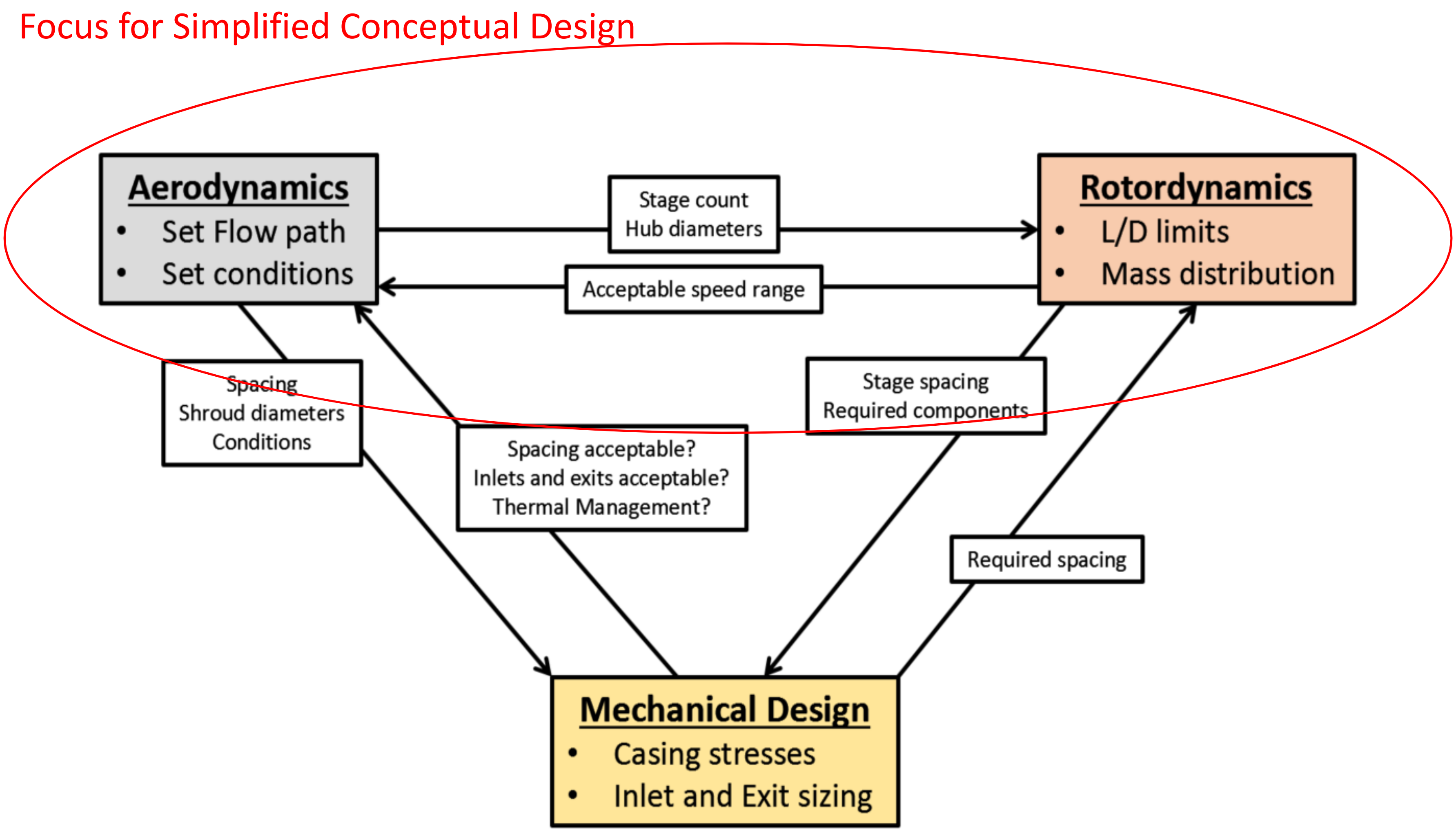
Off Design RCBC Analysis

- Sweeps Used to identify optimal off-design operating conditions
- RCBC Parameters of interest include
  - Bypass Compressor split fraction
  - Main Compressor inlet pressure (system mass analogue)
  - Net Power
- Sweeps computed at constant
  - Turbine inlet temperature
  - Cooler exit temperature
- Simulations provide correlations for system operation and control system development
- Component limitations determine which data points are feasable



Machinery Design Considerations

Mechanical Design Considerations



Focus for Simplified Conceptual Design

Aerodynamics
- Set Flow path
- Set conditions

Stage count
Hub diameters

Acceptable speed range

Rotordynamics
- L/D limits
- Mass distribution

Spacing
Shroud diameters
Conditions

Spacing acceptable?
Inlets and exits acceptable?
Thermal Management?

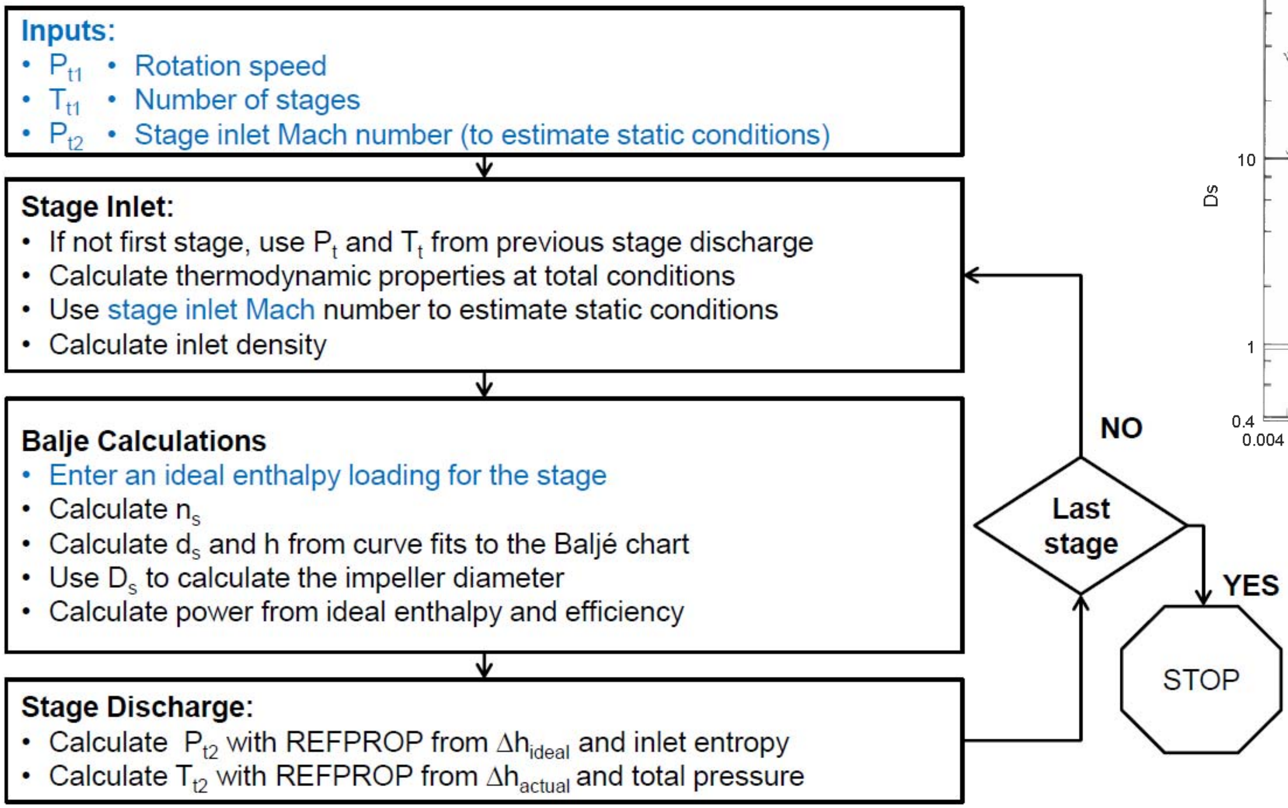
Stage spacing
Required components

Required spacing

Mechanical Design
- Casing stresses
- Inlet and Exit sizing

Turbomachinery Initial Sizing Methodology

Use experience-based charts for efficiency, specific speed, and specific diameter (Baljé Charts) to investigate optimal stage counts and speed.

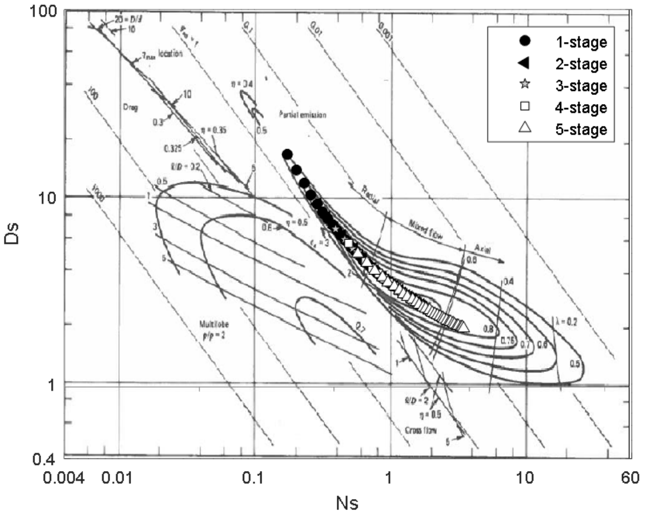


Inputs:
- P_{t1}
- T_{t1}
- P_{t2}
- Rotation speed
- Number of stages
- Stage inlet Mach number (to estimate static conditions)

Stage Inlet:
- If not first stage, use P_t and T_t from previous stage discharge
- Calculate thermodynamic properties at total conditions
- Use stage inlet Mach number to estimate static conditions
- Calculate inlet density

Balje Calculations
- Enter an ideal enthalpy loading for the stage
- Calculate n_s
- Calculate d_s and h from curve fits to the Baljé chart
- Use D_s to calculate the impeller diameter
- Calculate power from ideal enthalpy and efficiency

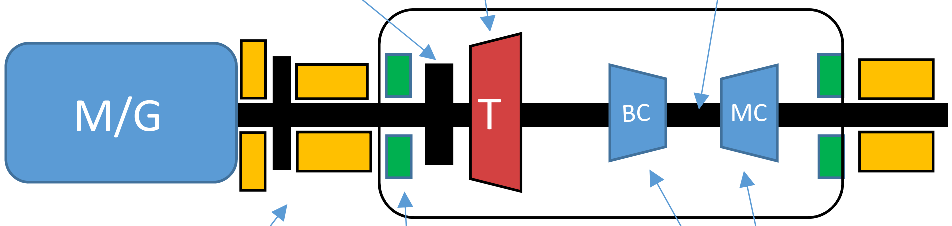
Stage Discharge:
- Calculate P_{t2} with REFPROP from Δh_{ideal} and inlet entropy
- Calculate T_{t2} with REFPROP from Δh_{actual} and total pressure



Conceptual Aerodynamic Sizing

- Compressor Sweeps
  - Baljé-based 0D design
  - Efficiencies corrected for expected leakage of division wall, balance piston, eye seals, and hub seals.
- Turbine Sweeps
  - 1D design with NASA RTD code
  - All seal leakage losses included

Turbomachinery Components



Turbine Stage

Balance Piston

Division
Wall Seal

Journal and
Thrust Bearings

Shaft End Seals

Compressor Stages

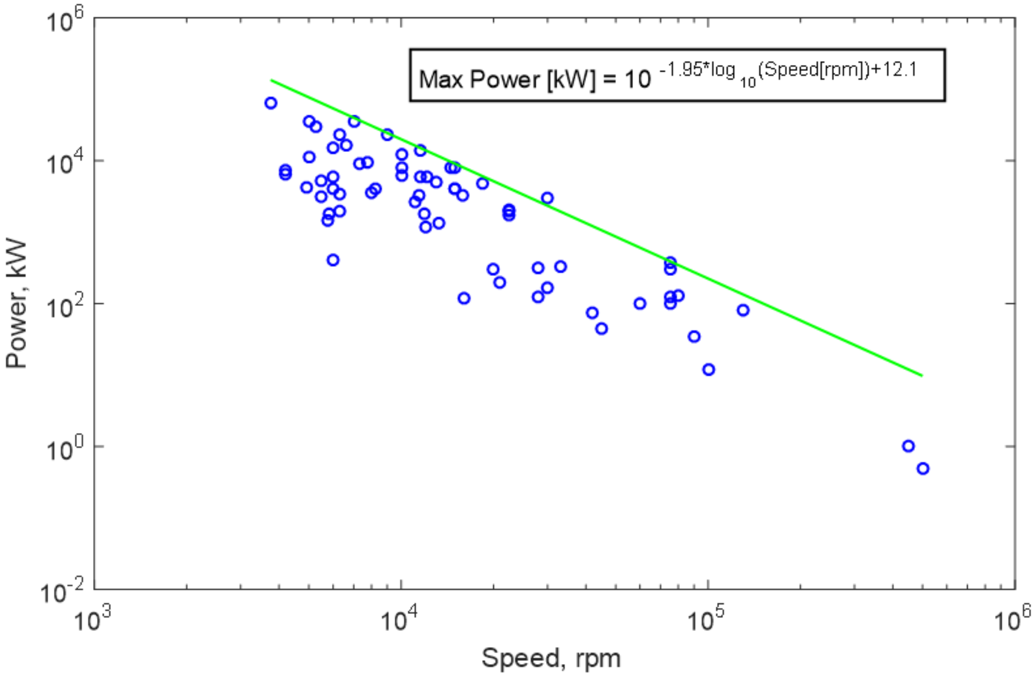
Component	Shaft Length Estimate	Shaft Diameter Estimate
Aero Stage	1-1.2 tip diameters (radial)	From aero sizing hub diameter
Division Wall	0.5 hub diameters	From aero sizing hub diameter
Balance Piston	0.5 piston diameter	Average eye diameter from aero stages
Thermal Management	0.3-0.4 shaft diameters per 100 °C temperature difference	Match with other shaft components
Dry Gas Seal	0.4-1.5 shaft diameters (longer for smaller seals)	Assume from aero hub diameter
Journal Bearings	1.0 shaft diameters	Minimum of aero hub diameter or diameter for 110 m/s surface speed
Thrust Bearing Disk	0.2-0.3x disk diameter	1.2x Average aero tip diameter

Turbomachinery Component Limits

Component	Limits	Notes
Rotordynamics	Conceptual Limit L/D < 9-12	Detailed rotordynamic analysis required!
Shaft Stresses	5.0 SF on yield 1.5 SF on creep	Yield SF considers bending, dynamics.
Balance Piston	-	Typically on one end to minimize sealing pressures
Thermal Management	0.3-0.4 inch per 100 °C	Goal: Axial temperature gradient
Dry Gas Seal	Max speed 55 kprm; Max temperature 230 °C	
Oil Film Bearings	Max surface speed of 100-110 m/s	
Coupling	Generally not a limiting component	Rigid couplings may be required for large, high-power applications

Generator and Gearbox Limits

- Can use gearbox to synchronous generator
  - Max high-speed shaft is ~55krpm for single stage gearbox
  - Higher speeds for more complex gearboxes, also higher losses
  - Gearbox a possibility up to ~50 MW shaft power
  - Gearbox efficiency ~96-98%
- High-speed generator is possible, but will typically impose speed limits based on power
- Integral high-speed machinery with immersed generator likely to have high windage losses.



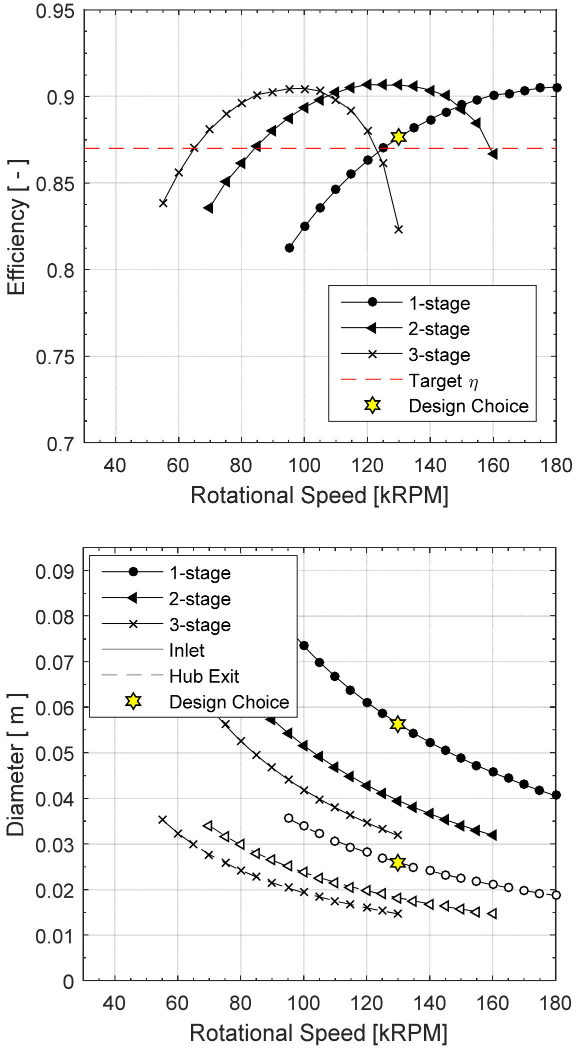
Case Study Results

Cycle Conditions

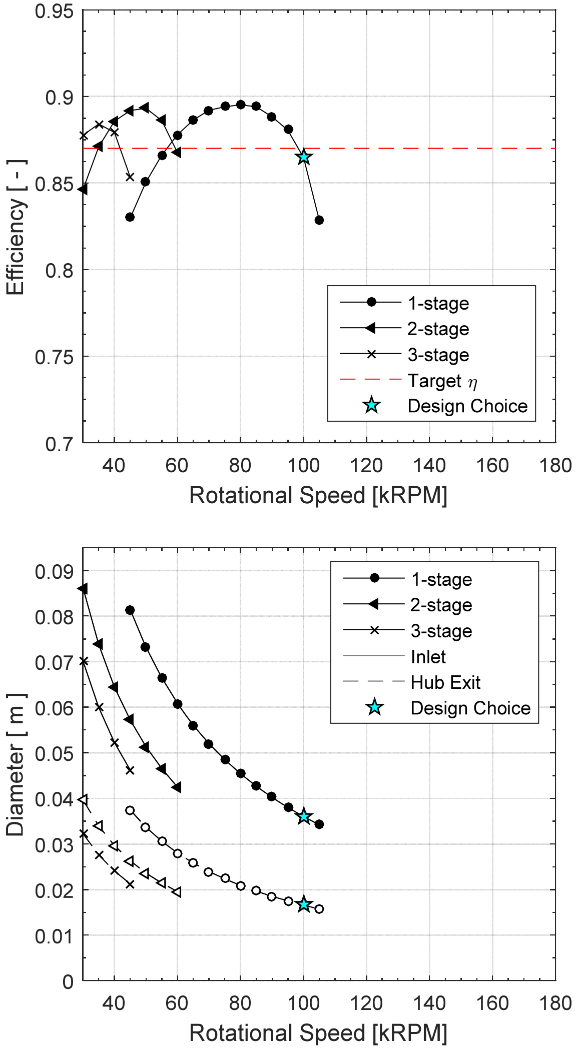
			Cycle Case			
			C1	C2	C3	C6
Main Compressor	Pt1	bar	89.00	89.00	89.00	89.00
	Tt1	C	34.98	34.98	34.98	34.98
	Pt2	bar	220.85	220.85	220.85	220.85
	W	kg/sec	4.91	4.48	4.44	5.32
	Isentropic Efficiency	%	65.00	80.00	85.00	64.00
Bypass Compressor	Pt1	bar	89.99	89.99	89.99	89.99
	Tt1	C	69.61	66.56	66.04	69.41
	Pt2	bar	219.53	219.53	219.53	219.53
	W	kg/sec	2.10	1.92	1.90	2.28
	Isentropic Efficiency	%	60.00	75.00	75.00	67.00
Drive Turbine	Pt1	bar	214.95	214.95	214.95	214.95
	Tt1	C	699.99	699.99	699.99	699.99
	Pt2	bar	166.16	175.44	176.58	165.49
	Tt2	C	664.98	672.26	673.14	666.59
	W	kg/sec	7.01	6.40	6.34	7.60
	Power	kW	296.00	215.00	206.00	306.00
	Isentropic Efficiency	%	87.50	87.50	87.50	82.00
Power Turbine	Pt1	bar	166.16	175.44	176.58	165.49
	Tt1	C	664.98	672.26	673.14	666.59
	Pt2	bar	91.26	91.26	91.26	91.26
	Tt2	C	587.23	587.21	587.20	594.76
	W	kg/sec	7.01	6.40	6.34	7.60
	Power	kW	643.00	643.00	643.00	643.00
	Isentropic Efficiency	%	88.50	88.50	88.50	82.00
Cycle	Thermal Efficiency	%	44.60	47.80	48.20	42.60
	Shaft Power	kW	643.00	643.00	643.00	643.00
	Thermal Input	kW	1442.94	1346.19	1334.26	1508.16

C2: Turbine Sizing

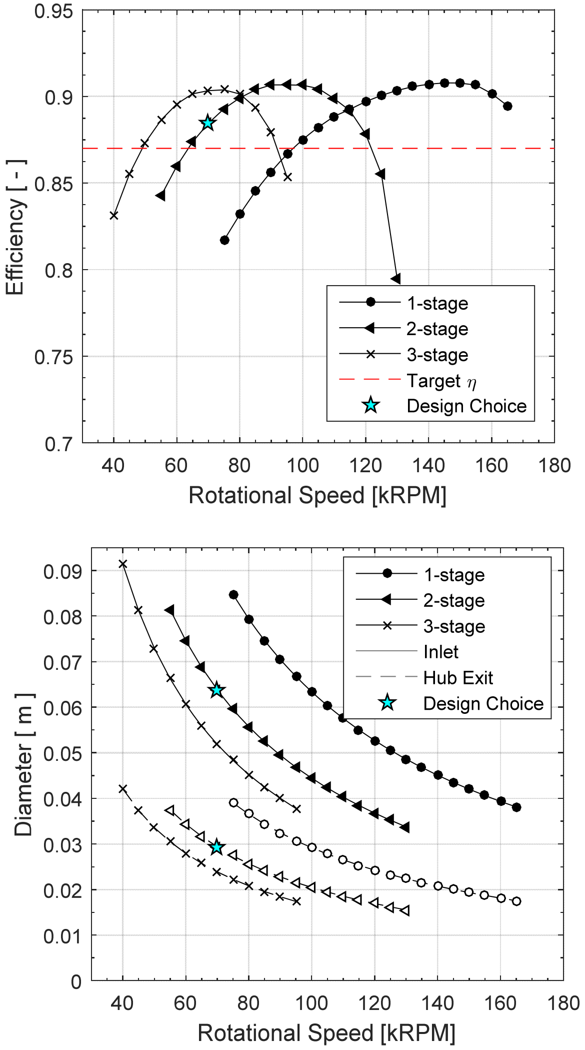
Single Shaft Turbine



Drive

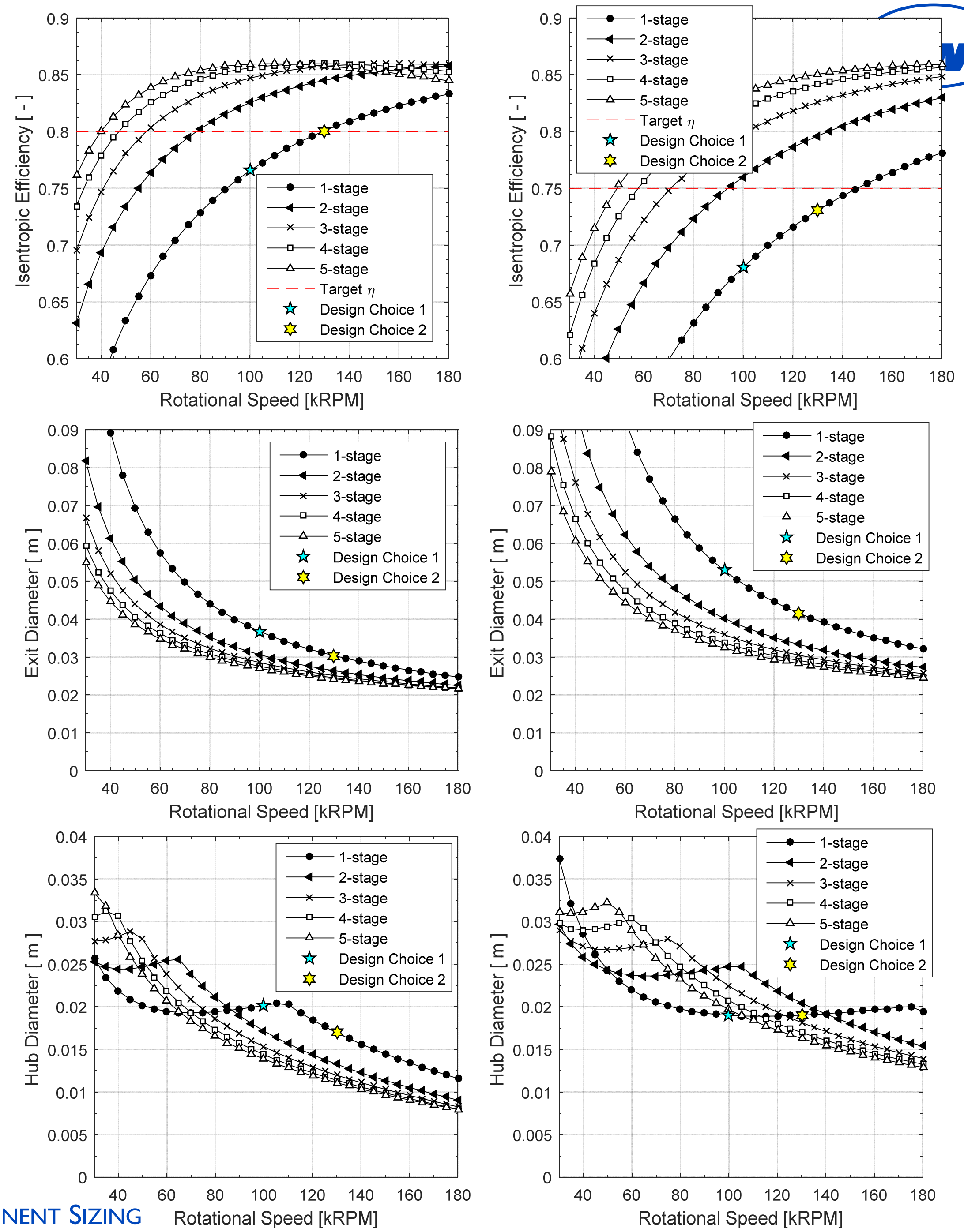


Power

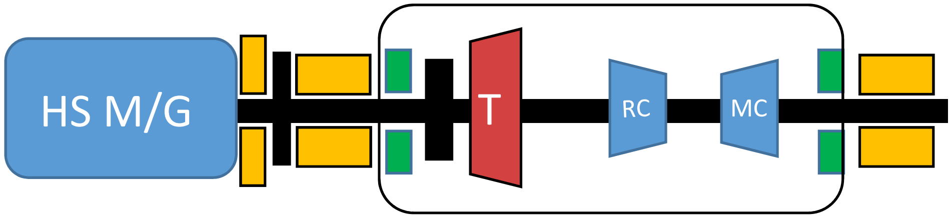


C2: Compressor & Bypass Compressor Sizing

- Main compressor on left, Bypass compressor on right
- Results show that peak efficiencies occur at very high speeds
- Two design speeds chosen based on motor/generator speed limits and drive turbine matching



Layout 1



130 krpm single-casing unit

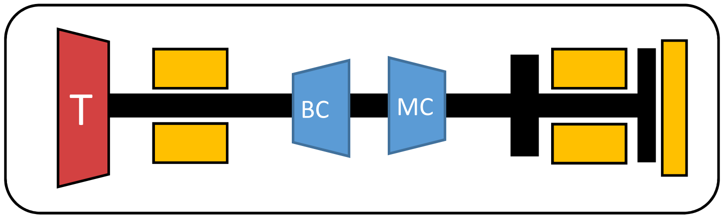
Component	Units	
Main Compressor Efficiency	-	0.79
Bypass Compressor Efficiency	-	0.73
Turbine Efficiency	-	0.88
Main Compressor Hub Diameter	mm	17
Bypass Compressor Hub Diameter	mm	20
Turbine Hub Diameter	mm	26
Bearing Span	mm	332
Bearing Surface Speed	m/s	109
L/D	-	14.9
Min Yield Safety Factor	-	6.0 (at DE bearing)
Min Creep Safety Factor	-	4.6 (at turbine)

Layout 1 - Discussion

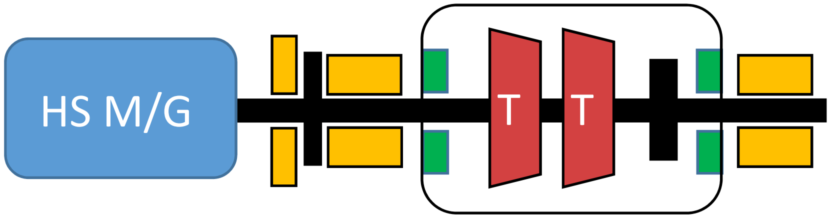
- Layout 1 maximizes machinery speeds, efficiency and minimizes stage count and size
- Assumed operating speed exceeds existing capability of 500 kW motor/generator and also of dry gas seals -> significant technology development/risk
- Shaft L/D very high -> likely rotordynamic challenges even with minimized stage count
- Shaft torque and bearing surface speeds acceptable
- Next layout: Reduce speeds to within motor/generator and seal capabilities

Layout 2

100 krpm turbo-compressor



55 krpm turbo-generator



Component	Units	Turbo-Compressor	Turbo-Generator
Main Compressor Efficiency	-	0.77	-
Bypass Compressor Efficiency	-	0.68	-
Turbine Efficiency	-	0.88	0.85
Main Compressor Hub Diameter	mm	21	-
Bypass Compressor Hub Diameter	mm	20	-
Turbine Hub Diameter	mm	20	37
Bearing Span	mm	212	413
Bearing Surface Speed	m/s	99	104
L/D	-	10.5	11.2
Min Yield Safety Factor	-	18 (at turbine)	24.5 (at turbine)
Min Creep Safety Factor	-	4.1 (at turbine)	5.6 (at turbine)

Layout 2 - Discussion

- Layout 2 splits the turbine to maximize compressor speed and efficiency while keeping speeds within component limits
- Efficiencies slightly lower than Layout 1
- Concept assumes immersed bearings for turbo-compressor
  - Likely requires component development and validation of bearing performance and careful minimization and prediction of thrust loads
- Shaft L/D values are high but reasonable. Will need to minimize during detailed design
- Shaft torque and bearing surface speeds good
- Next layout: Reduce all speeds to allow end seals and oil bearings

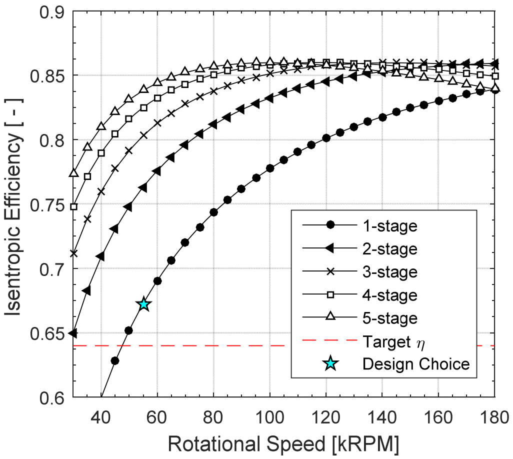
C6 Reduced Cycle Efficiency, Minimize Tech Gaps & Risk

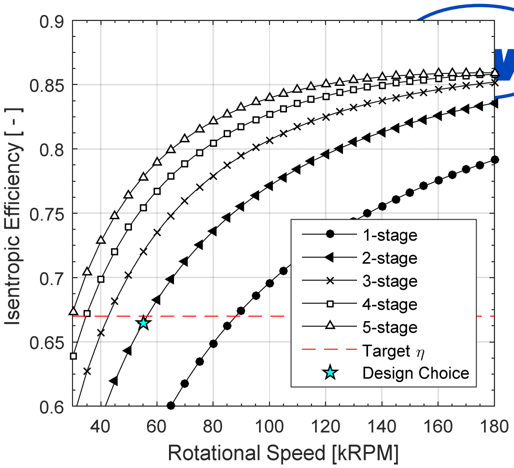
55,000 RPM

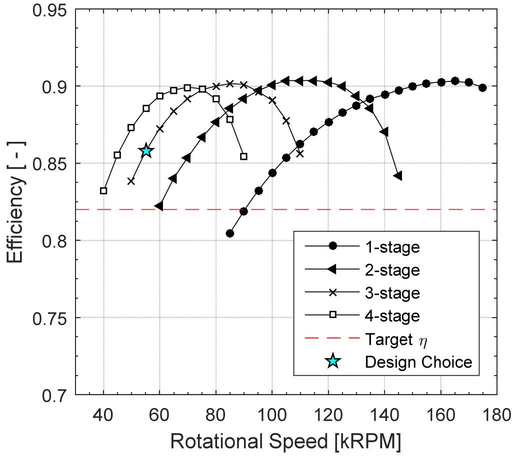
3-stage turbine

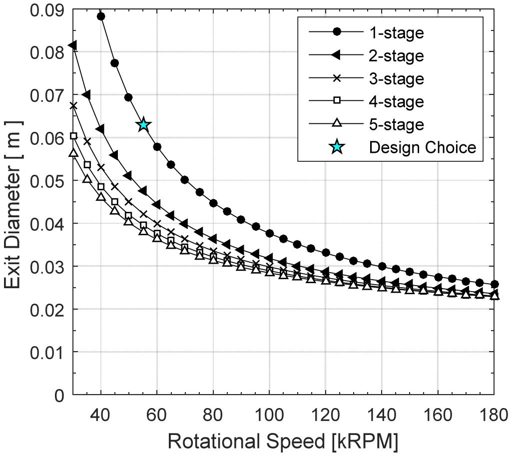
1-stage main compressor

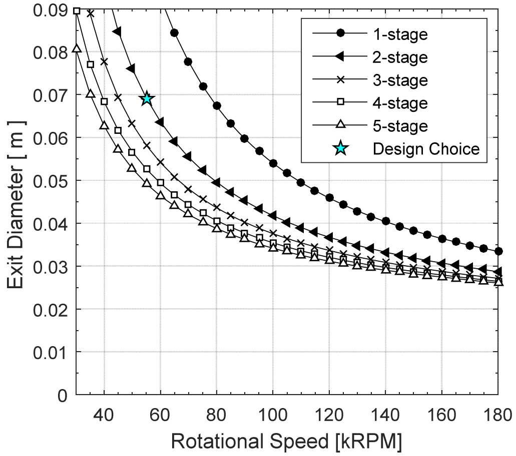
2-stage bypass compressor

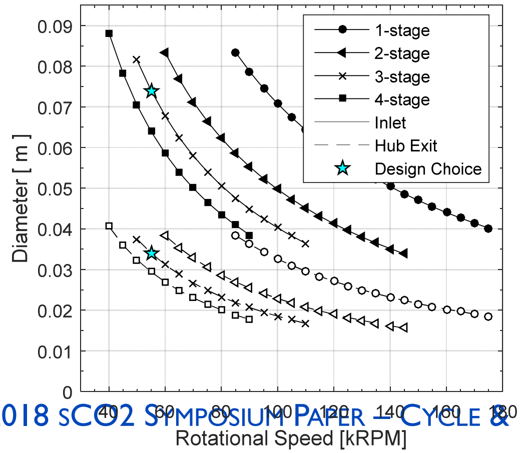


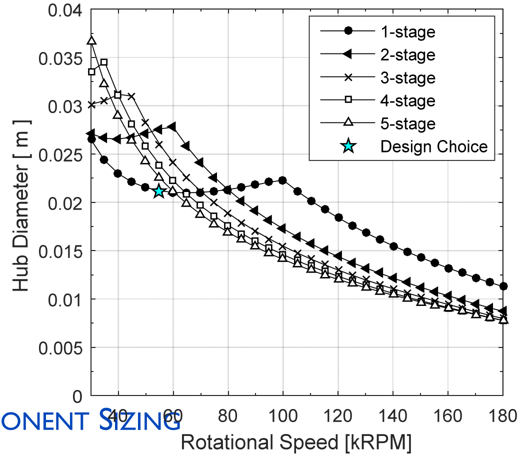


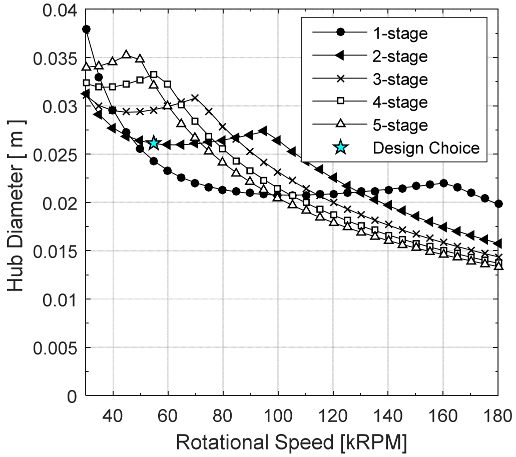




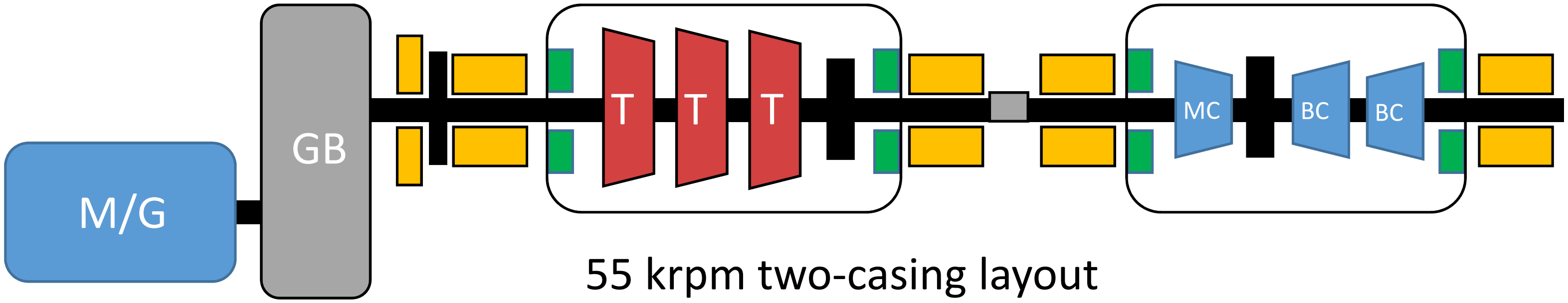








Layout 3



55 krpm two-casing layout

Component	Units	Compressor Unit	Turbine Unit (2-stage)	Turbine Unit (3-stage)
Main Compressor Efficiency	-	0.67	-	-
Bypass Compressor Efficiency	-	0.65	-	-
Turbine Efficiency	-	-	0.81	0.86
Main Compressor Hub Diameter	mm	21	-	-
Bypass Compressor Hub Diameter	mm	26	-	-
Turbine Hub Diameter	mm	-	42	34
Bearing Span	mm	316	447	455
Bearing Surface Speed	m/s	67	95	95
L/D	-	13.0	10.7	13.5
Min Yield Safety Factor	-	16.7 (at DE bearing)	17.4 (at GB side bearing)	17.4 (at GB side bearing)
Min Creep Safety Factor	-	-	8.1 (at turbine)	4.3 (at turbine)

Layout 3 - Discussion

- Layout 3 is the slowest and largest turbomachinery option, but minimizes development risk and effort
- Efficiencies significantly lower than Layout 1
- Can replace gearbox / generator with a high-speed motor/generator
- Shaft L/D values are high (particularly for the compressor unit). Will need to perform further aero-dynamic/rotordynamic analysis and optimization during detailed design
- Shaft torque and bearing surface speeds good

Case Studies - Discussion

- Efficient cycle and machinery design methodology presented for evaluating sCO2 cycle options within practical component limits
- 500 kW case study highlights the strong influence of component limits on cycle performance at this scale