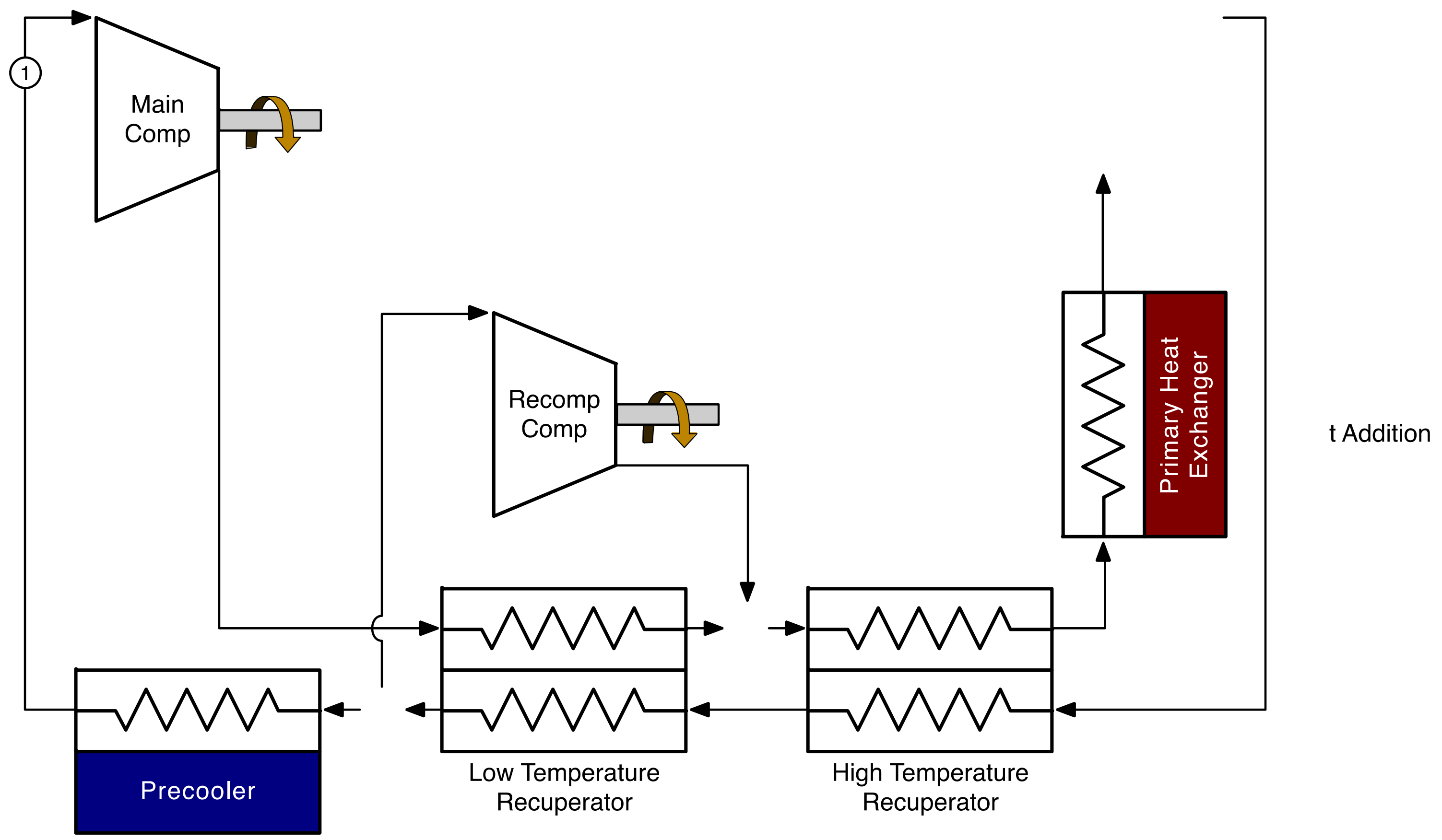
Development of a Flexible Modeling Tool for Predicting Optimal Off-Design Performance of Simple and Recompression Brayton Cycles

John Dyreby

The 4th International Supercritical CO_2 Power Cycles Symposium

September 9, 2014

Recompression Cycle



Need for Fast and Flexible Off-Design Models

- There are many open questions about SCO_2 power cycles, such as:
  - How do the cycles operate under off-design conditions?
  - How should these cycles be controlled?
  - What is the best design?

- The answers to these questions are specific to the application being considered.

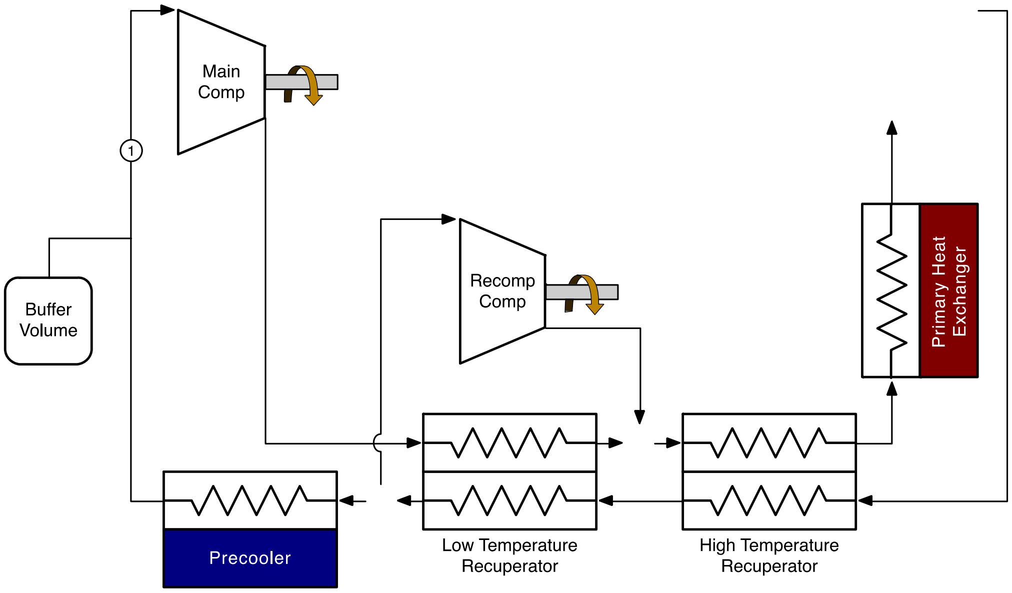
- The answer to "what is the best design?" is very specific to the economics of the application being considered.

- Any economic analysis requires consistent and computationally efficient performance estimates.

Need for Fast and Flexible Off-Design Models

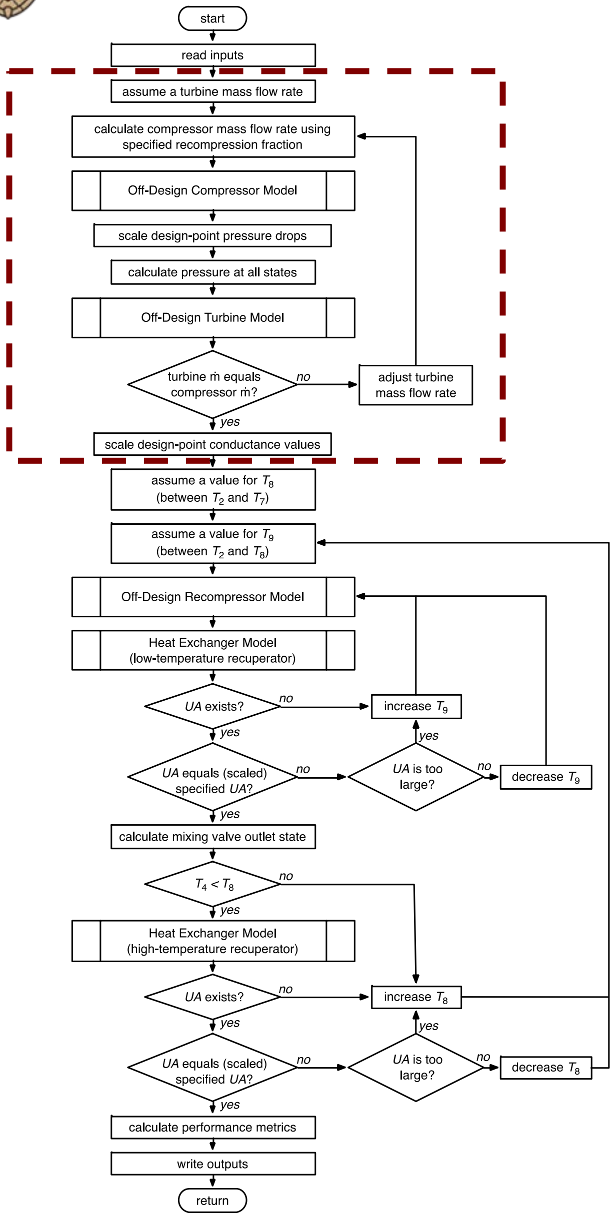
- The possible SCO_2 cycle applications are diverse:
  - Large-scale power generation (axial turbines, large hxrs)
  - Small-scale, modular power generation (radial turbines, small hxrs)
  - Waste heat recovery (Echogen Power Systems)
  - Operation in arid climates (CSP in southwestern United States)
  - Operation in temperate climates (nuclear in France)
- The modeling framework presented here provides the flexibility required to investigate these various applications.
- The developed cycle models are intended to be the core, innermost iteration of larger application-specific models.

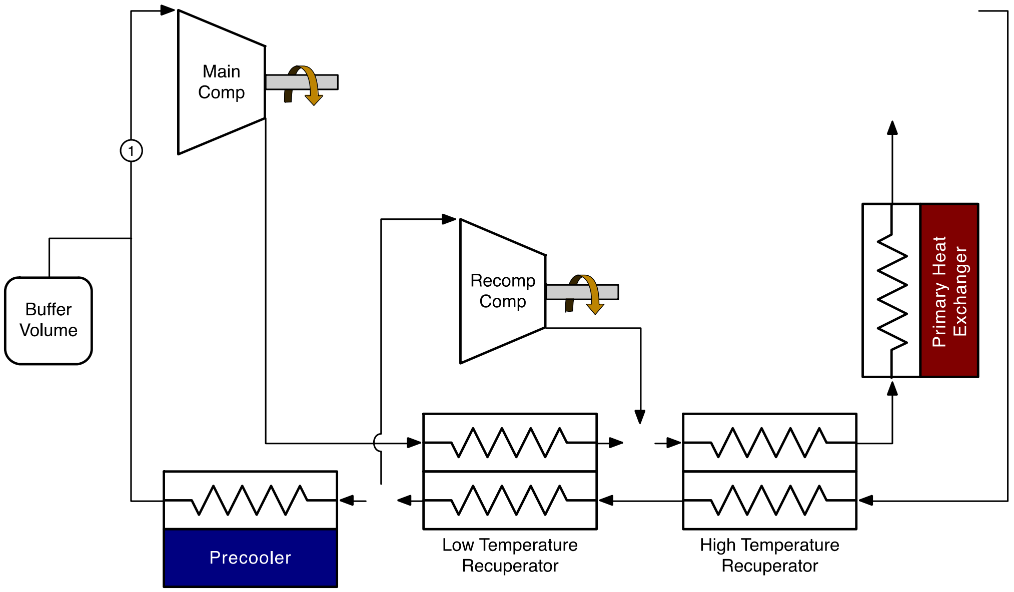
Off-Design Modeling Methodology



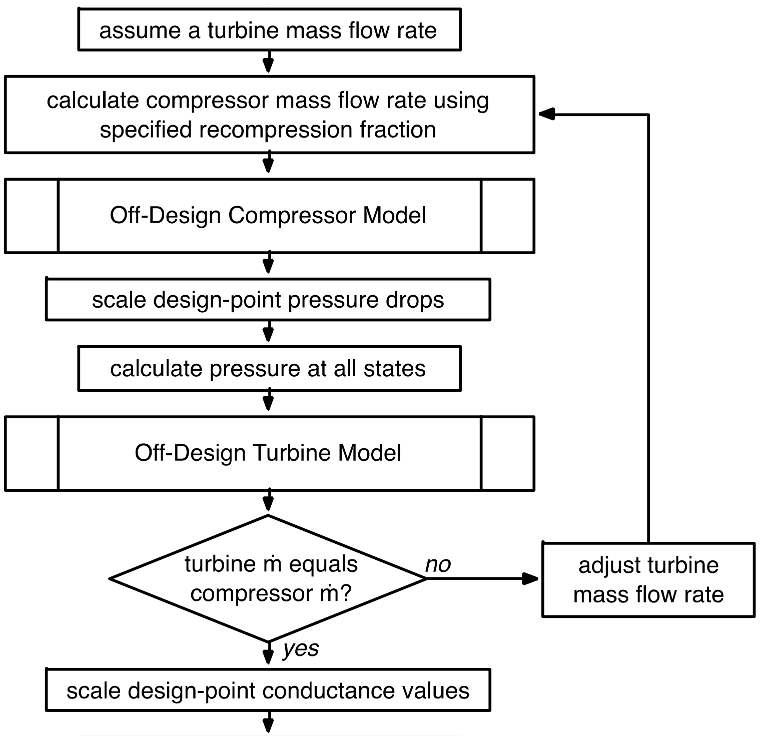
- Model inputs are shown in bold.
- Compressors, turbine, and heat exchangers are represented assuming “black box” behavior.
- The operating point is set by matching the head-flow behavior of the compressor with the flow resistance afforded by the turbine.

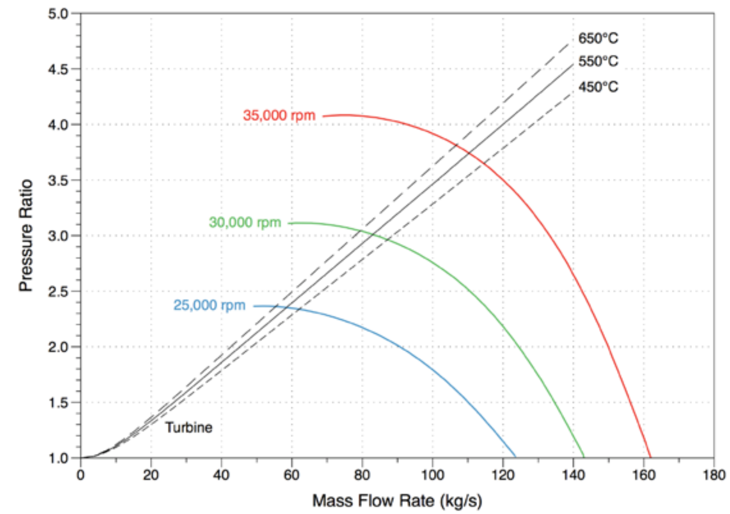
Off-Design Iteration Strategy

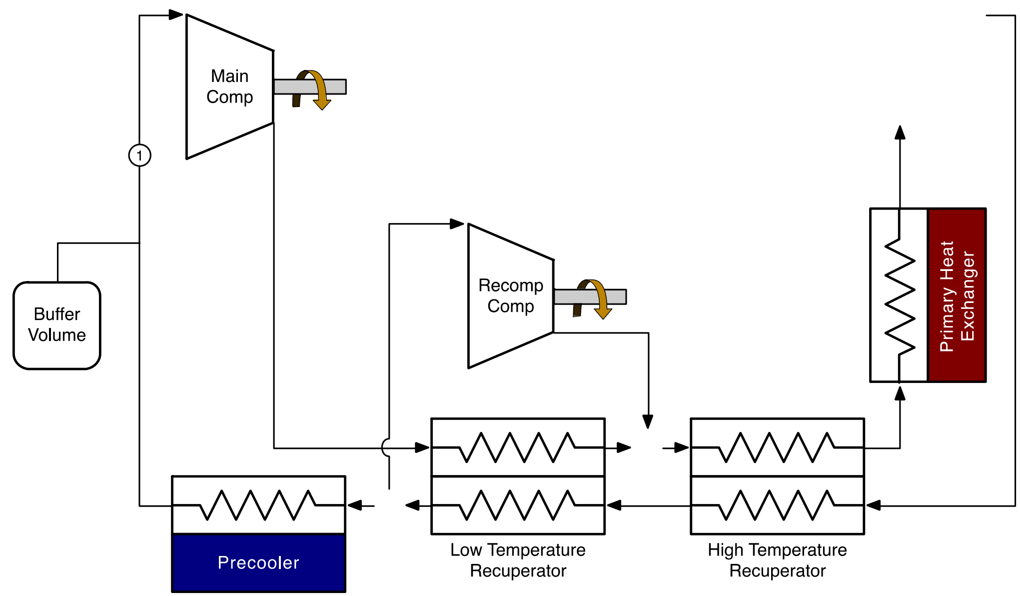




Off-Design Iteration Strategy







Modeling Framework

- The framework is written in Fortran and organized into modules.
- User-replaceable modules allow for application-specific analysis.

Module Name	Filename	Description
core	core.f90 (required)	Defines a number of user-defined types and contains a number of subroutines and functions required by the design_point and off_design_point modules.
design_point	design_point.f90 (required)	Contains the system-level subroutines used to model cycles at the design point.
off_design_point	off_design_point.f90 (required)	Contains the system-level subroutines used to model cycles under off-design or part-load conditions.
heat_exchangers	scaling_hxr.f90 (may be replaced)	Defines the functions responsible for scaling conductance and pressure drop under off-design mass flow rates.
compressors	snl_compressor.f90 snl_compressor_tsr.f90 (may be replaced)	Contains compressor and recompressor sizing and performance subroutines based on the SNL compressor.
turbines	radial_turbine.f90 snl_radial_turbine.f90 (may be replaced)	Contains the turbine sizing and performance subroutines based on a radial turbine.
CO2_properties	module_CO2_properties.f90 CO2_RP_module.f90 (may be replaced)	Contains the required fluid property subroutines for carbon dioxide.

Component Models (heat_exchangers, compressors, turbines)

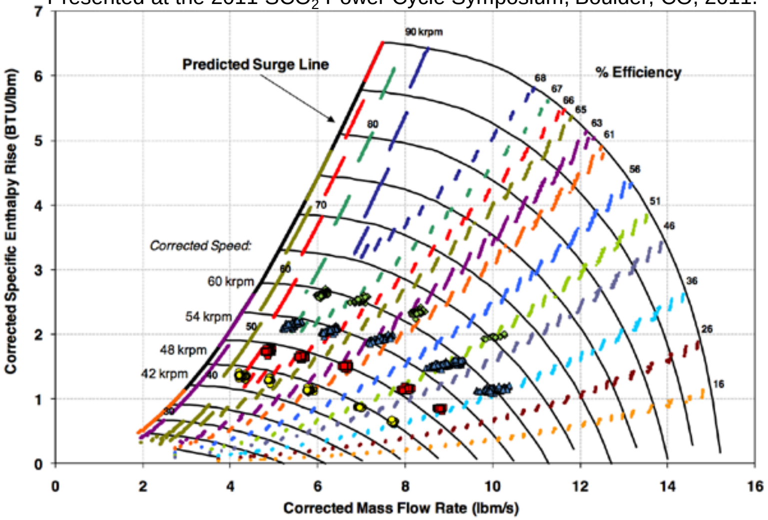
Implemented Component Models

- Compressor model is based on the radial compressor under investigation by Sandia National Laboratory (SNL).
- Turbine model assumes a a low-reaction radial turbine, with modifications based on the SNL turbine.
- Heat exchangers are represented by scaling conductance and pressure drop with off-design mass flow rate.

$$\Delta P = \Delta P_{design} \left(\frac{\dot{m}}{\dot{m}_{design}} \right)^{7/4} \qquad UA = UA_{design} \left(\frac{\dot{m}}{\dot{m}_{design}} \right)^{0.8}$$

Compressor Model

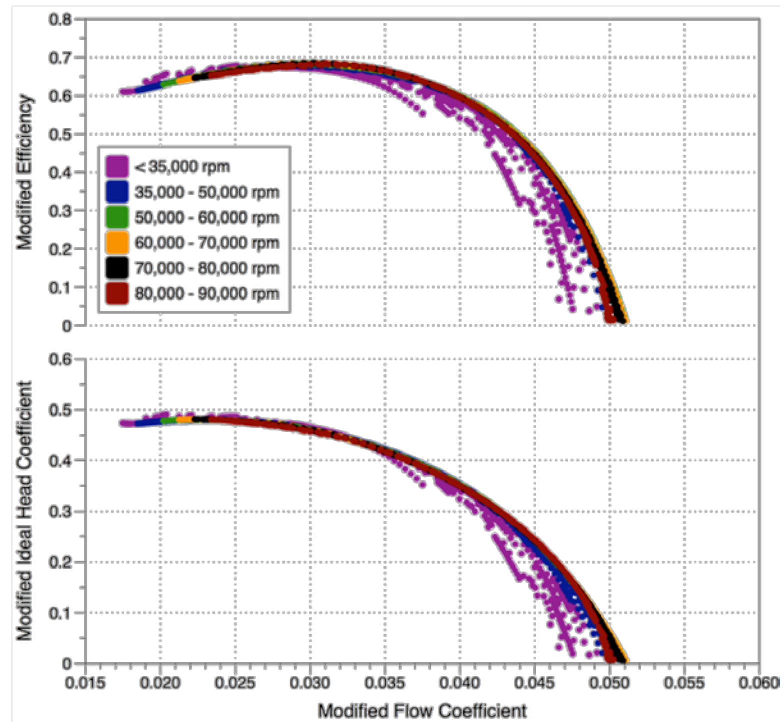
Wright et al., "Summary of the Sandia Supercritical CO_2 Development Program," Presented at the 2011 SCO_2 Power Cycle Symposium, Boulder, CO, 2011.

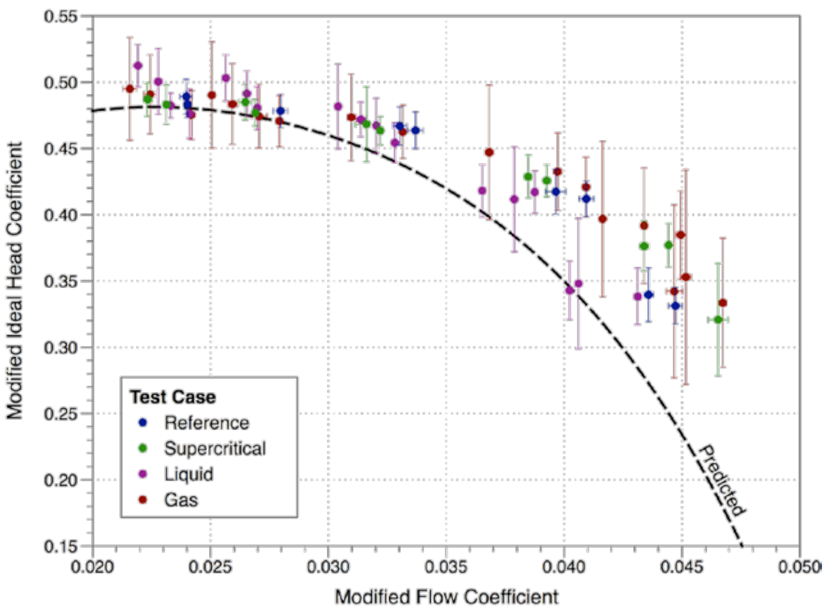


$$\phi^* = \frac{\dot{m}}{\rho U_c D_c^2}\left(\frac{N}{N_{design}}\right)^{1/5}$$

$$\psi_i^* = \frac{\Delta h_i}{U_c^2}\left(\frac{N_{design}}{N}\right)^{(20\phi^*)^3}$$

$$\eta^* = \eta\left(\frac{N_{design}}{N}\right)^{(20\phi^*)^5}$$

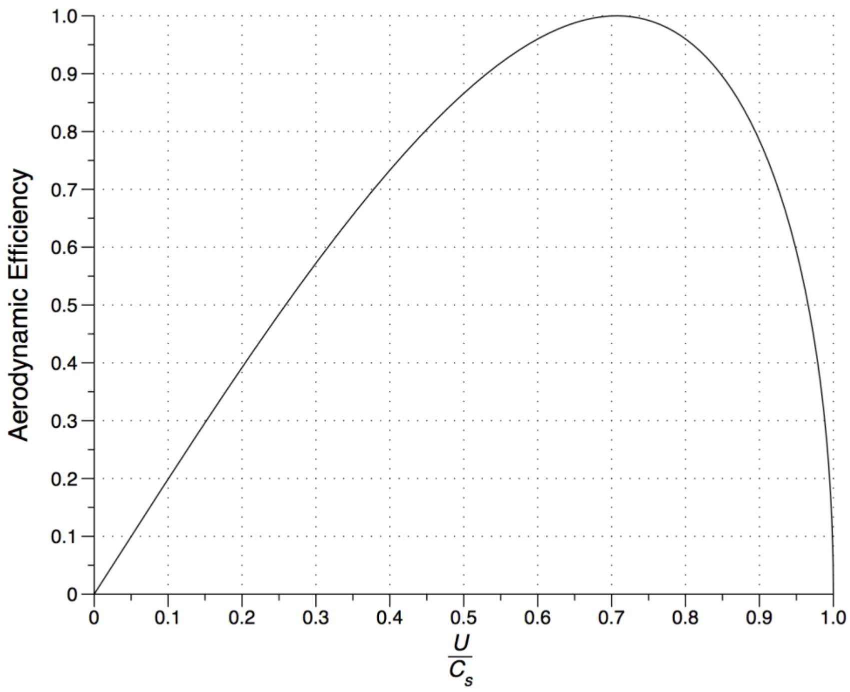




Low-Reaction Radial Turbine Model

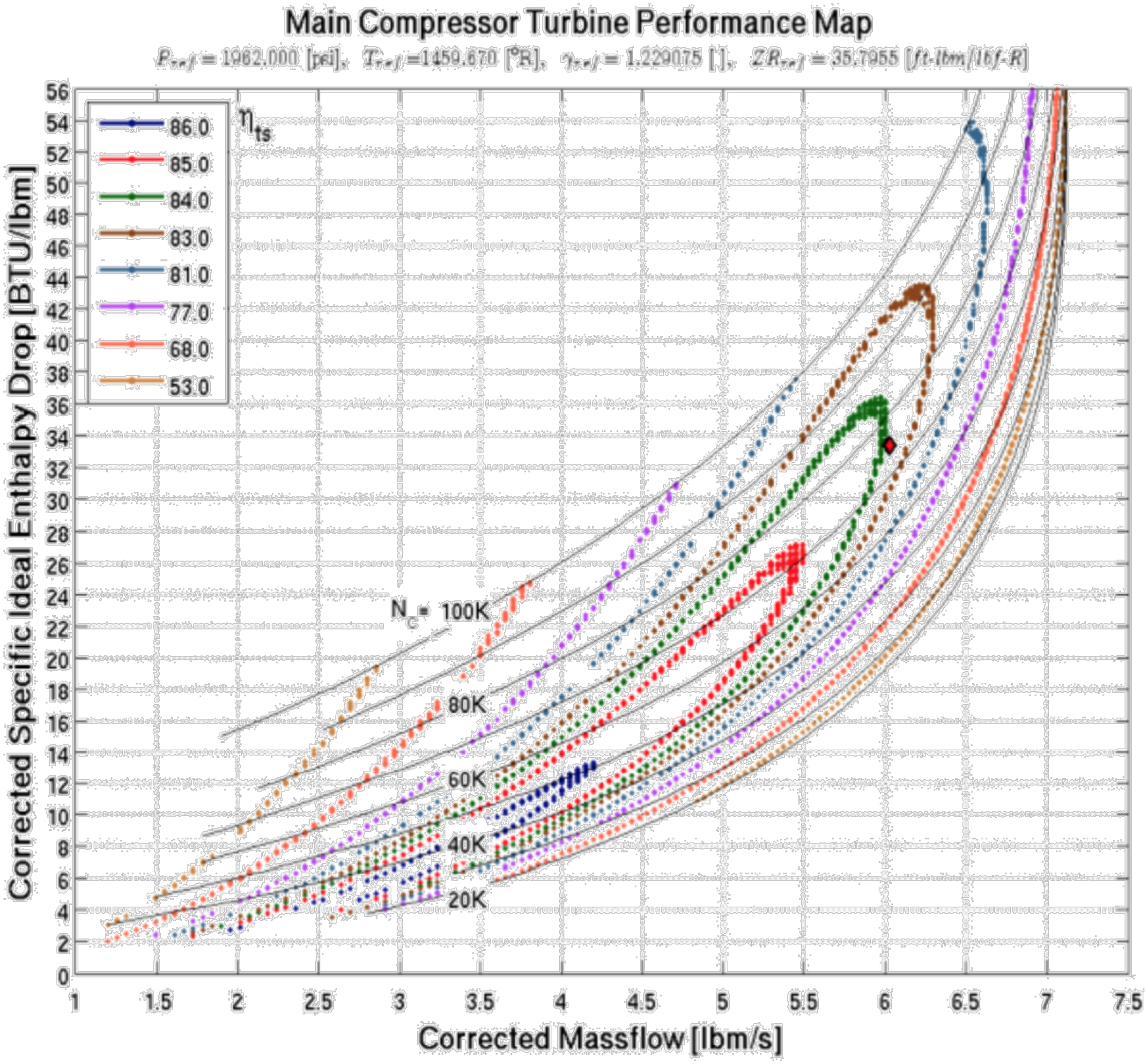
- Mass flow rate: $$\dot{m} = C_s \, A_{nozzle} \, \rho$$
- Spouting velocity: $$C_s = \sqrt{2\left(h_{turbine,in} - h_{turbine,out,i}\right)}$$
- Aerodynamic efficiency[1]: $$\eta_{turbine,aero} = 2\nu\sqrt{1-\nu^2}$$

$$\nu = \frac{U}{C_s}$$



[1] Chen, H. and N. C. Baines, "The Aerodynamic Loading of Radial and Mixed-Flow Turbines," Int. J. of Mech. Sci., Vol. 36, No. 1, pp. 63-79, (1994).

Performance Map for SNL Turbine

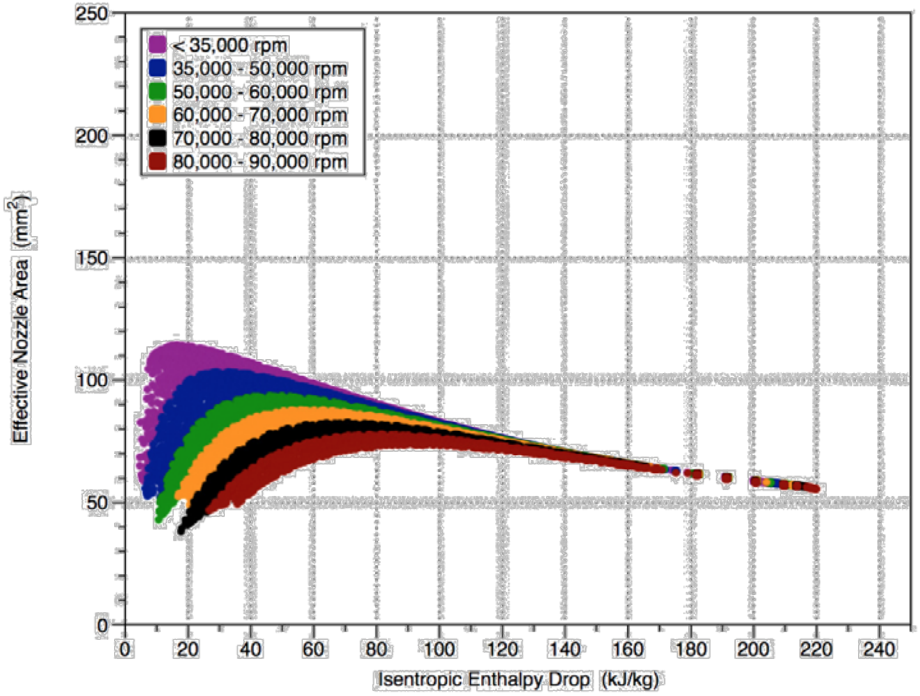


Wright et al., "Summary of the Sandia Supercritical CO_2 Development Program," Presented at the 2011 SCO_2 Power Cycle Symposium, Boulder, CO, 2011.

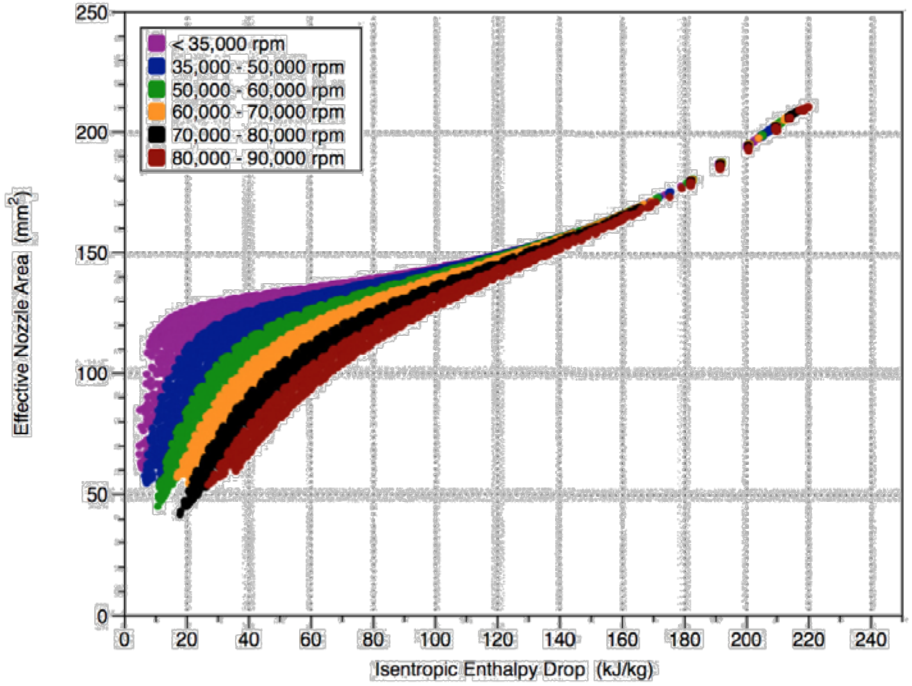
Turbine Model Modifications

$$\dot{m} = C_s \, A_{nozzle} \, \rho$$

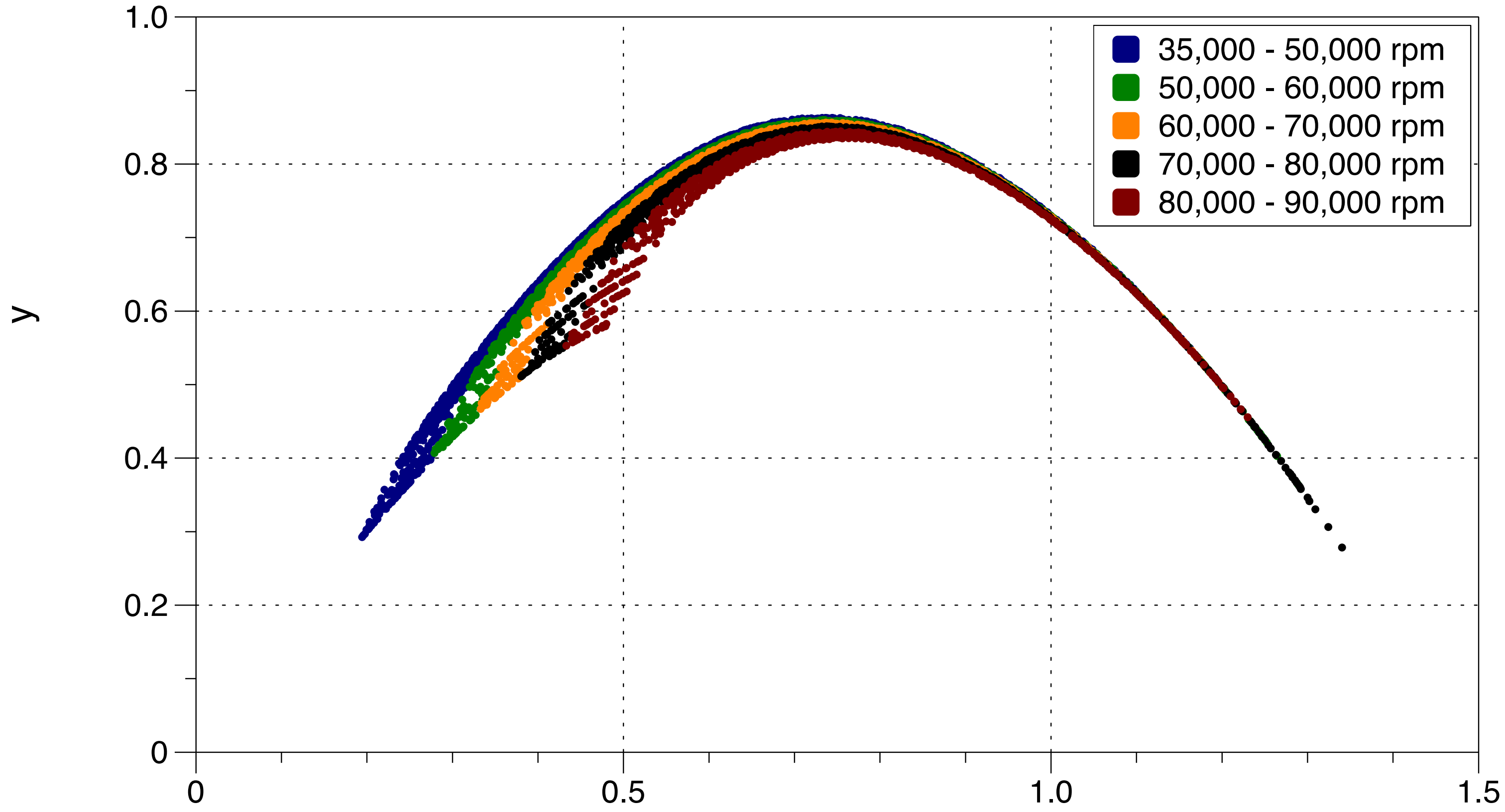
density at turbine inlet



density at turbine outlet



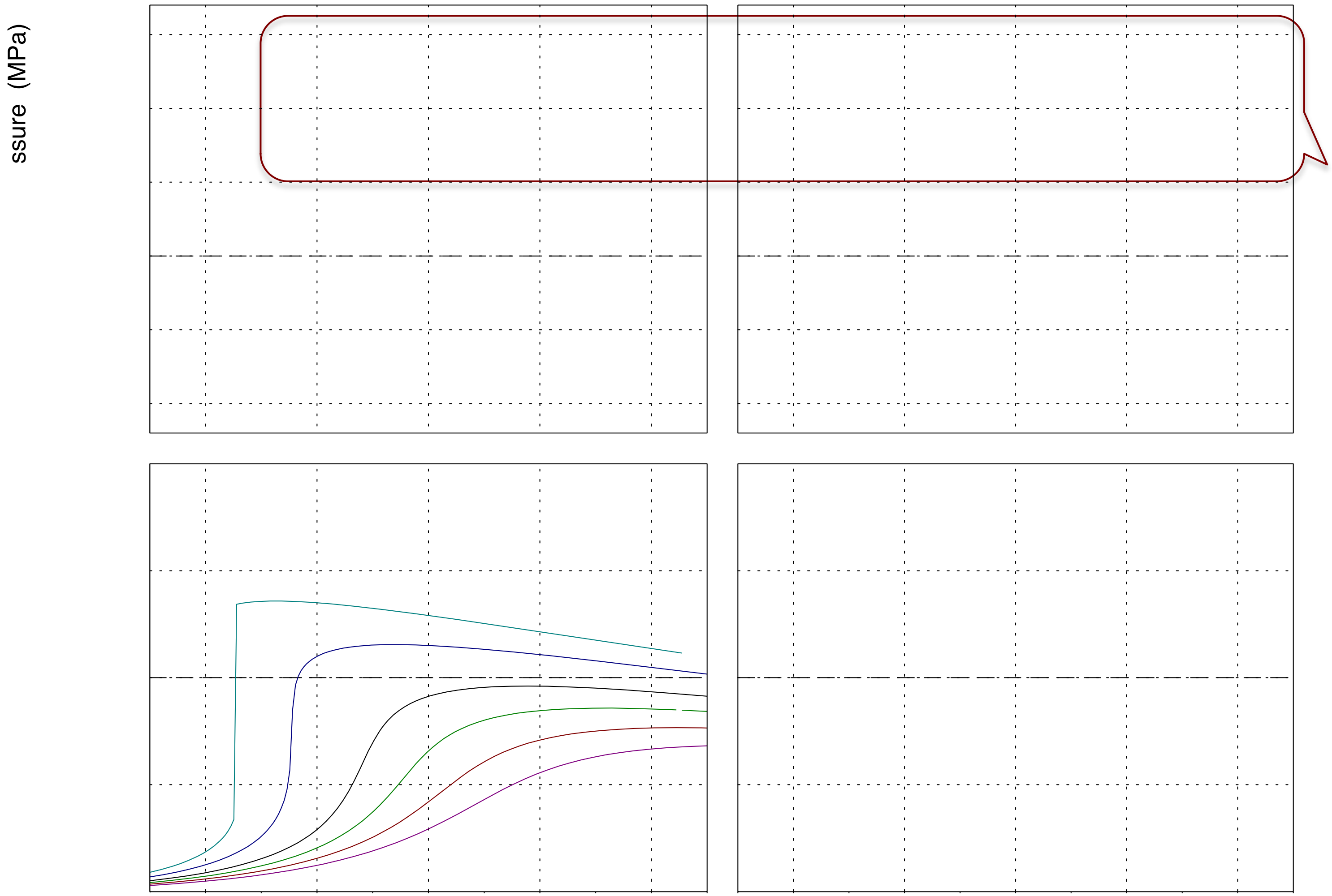
Turbine Model Modifications



Off-Design Analysis

Off-Design Operation for Two Designs

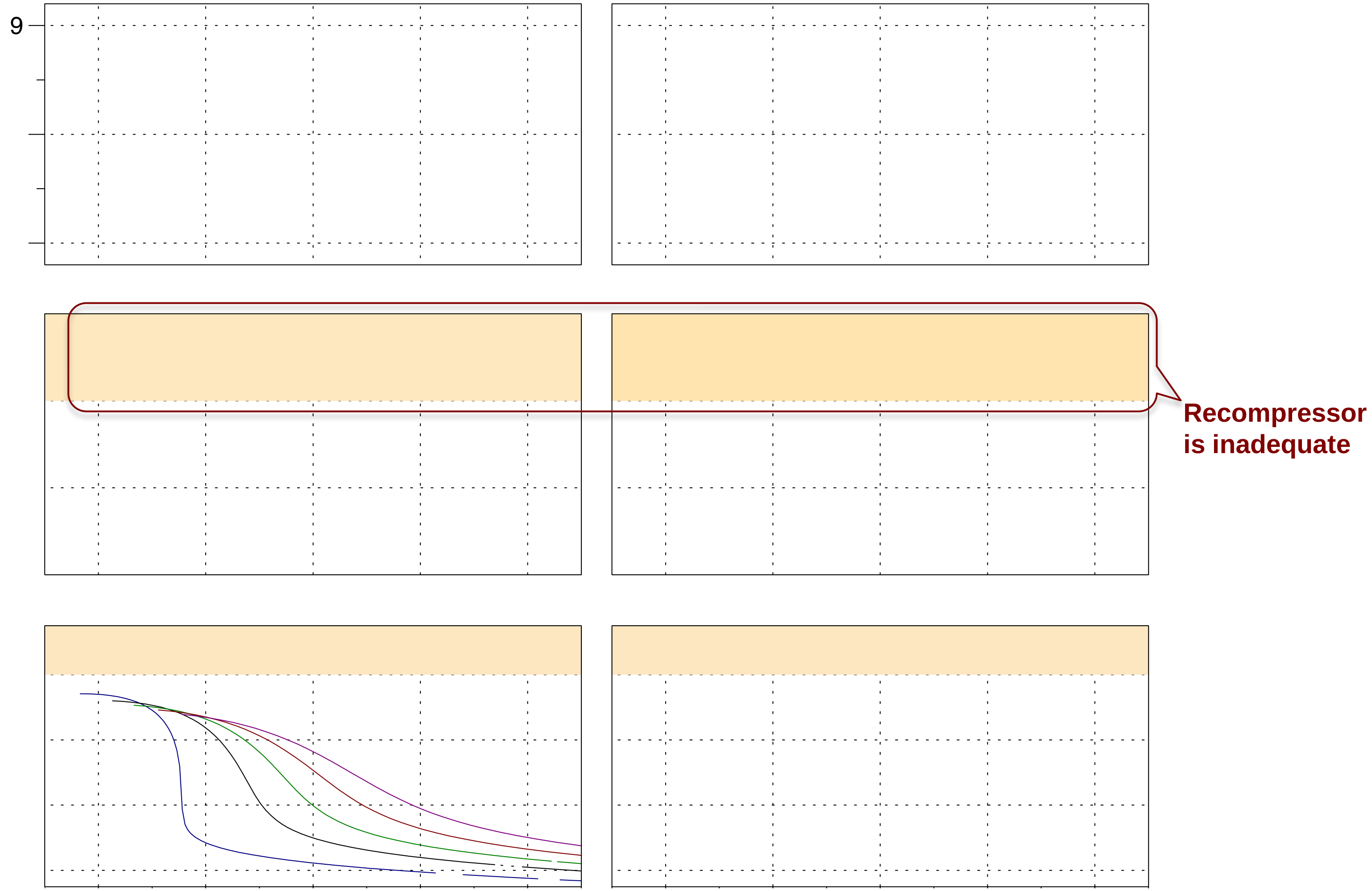
Main Shaft Speed and Recompression Fraction Fixed



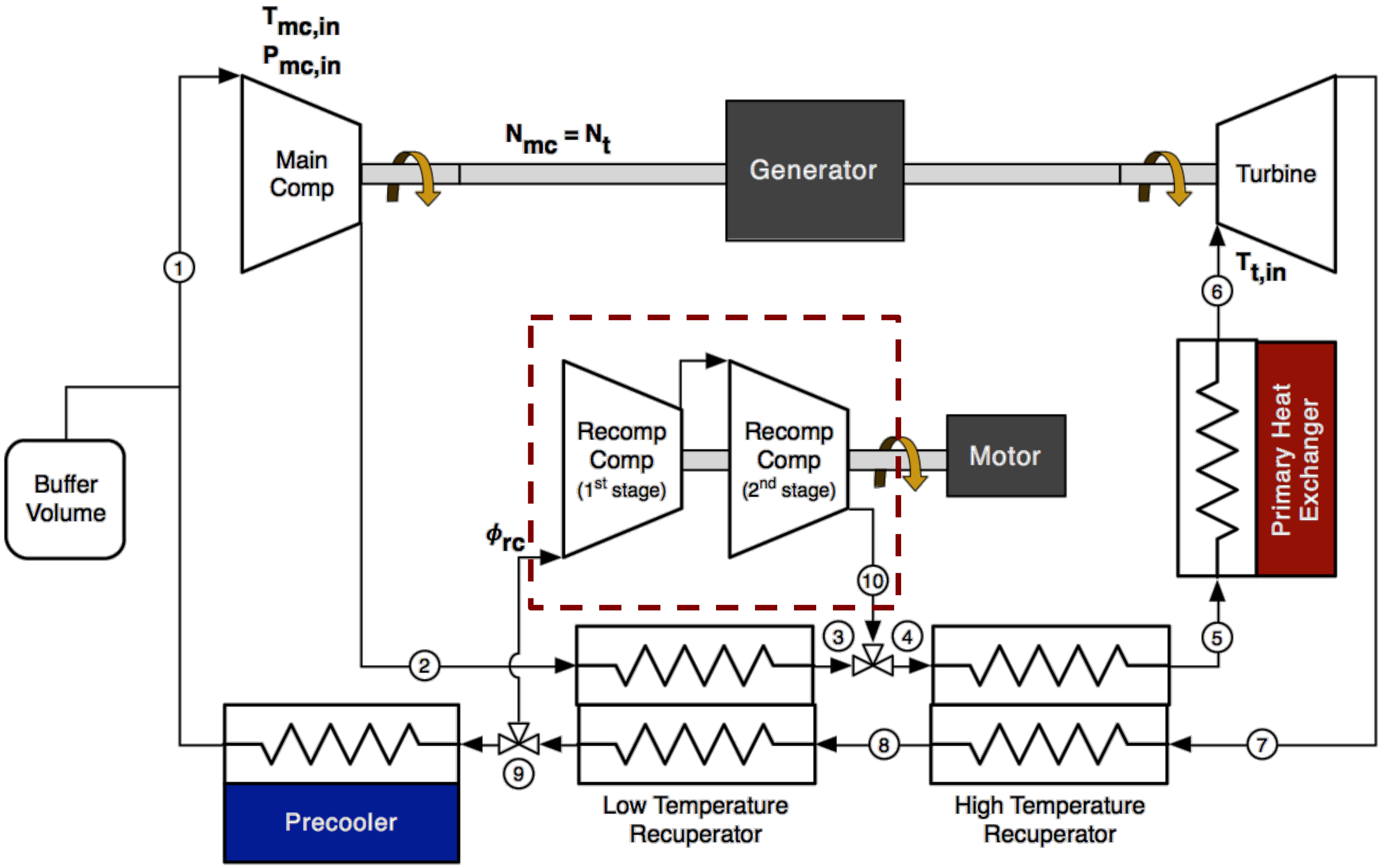
Unreasonable pressures for 25 MPa design

Off-Design Operation for Two Designs

Main Shaft Speed and Recompression Fraction Fixed



Cycle Configuration with Two-Stage Recompressor

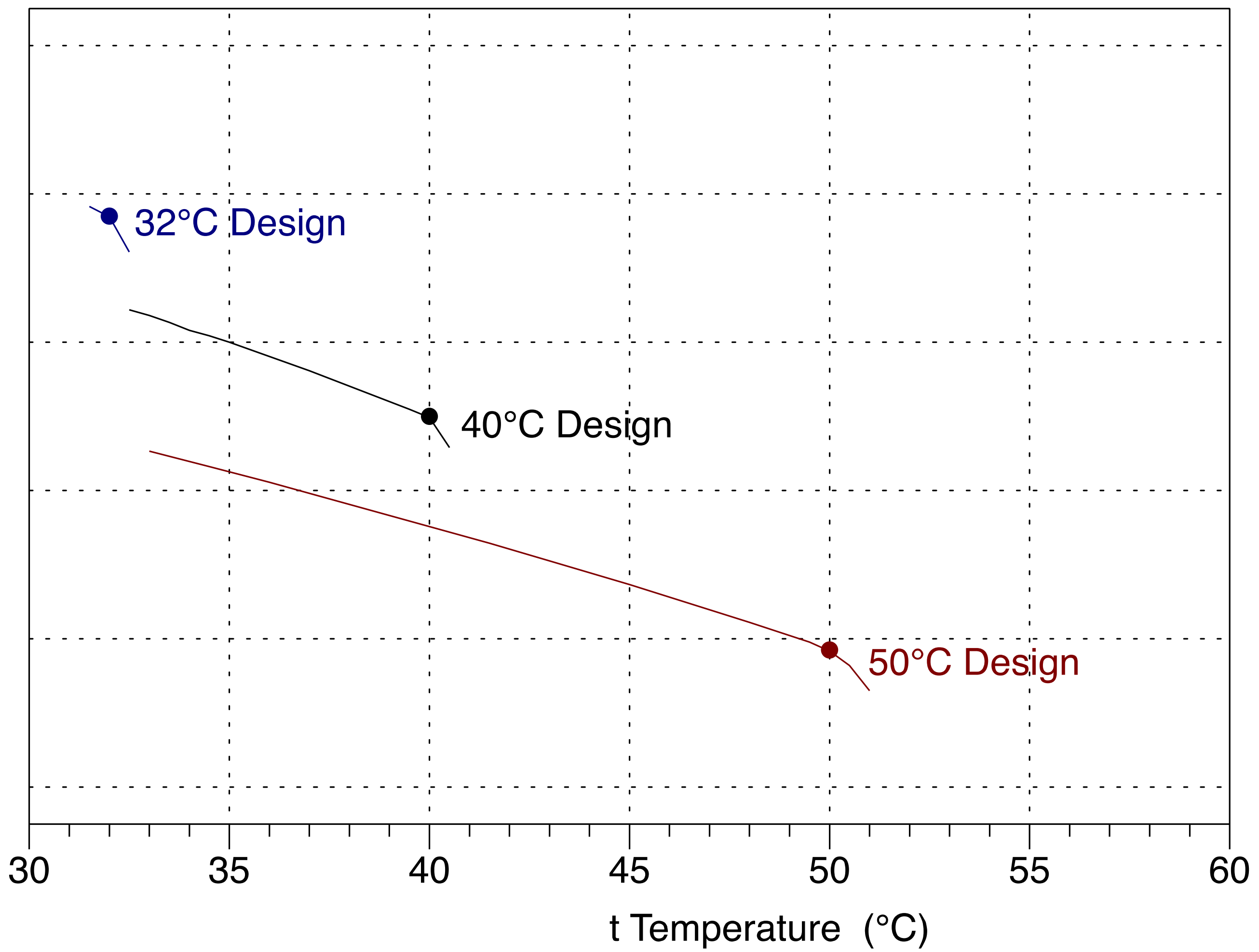


Three Designs of Interest

Power Output	10 MW		
Turbine Inlet Temperature	550°C		
Compressor Outlet Pressure	25 MPa		
Compressor Isentropic Efficiency	0.89		
Turbine Isentropic Efficiency	0.93		
Heat Exchanger Pressure Drops	1%		
Compressor Inlet Temperature	32°C	40°C	50°C
Compressor Inlet Pressure	7.7 MPa	9 MPa	10 MPa
LT Recuperator Conductance	1.74 MW/K	1.59 MW/K	1.52 MW/K
LT Recuperator Minimum ΔT	5.3°C	7.2°C	7.2°C
LT Recuperator Approx. Volume	80 m^3	50 m^3	40 m^3
HT Recuperator Conductance	1.26 MW/K	1.41 MW/K	1.48 MW/K
HT Recuperator Minimum ΔT	5.1°C	7.7°C	11.4°C
HT Recuperator Approx. Volume	40 m^3	35 m^3	35 m^3
Compressor Rotor Diameter	0.120 m	0.148 m	0.183 m
RC First Stage Rotor Diameter	0.162 m	0.162 m	0.157 m
RC Second Stage Rotor Diameter	0.137 m	0.141 m	0.139 m
Turbine Rotor Diameter	0.218 m	0.241 m	0.265 m
Turbine Effective Nozzle Area	1,140 mm^2	1,450 mm^2	1,790 mm^2
Main Shaft Speed	37,080 rpm	31,410 rpm	27,030 rpm
Recompressor Shaft Speed	34,620 rpm	32,570 rpm	32,790 rpm
Recompression Fraction	0.3752	0.3266	0.2578
Turbine Mass Flow Rate	96.8 kg/s	114.5 kg/s	134.2 kg/s
Thermal Efficiency	47.7%	45.0%	41.8%

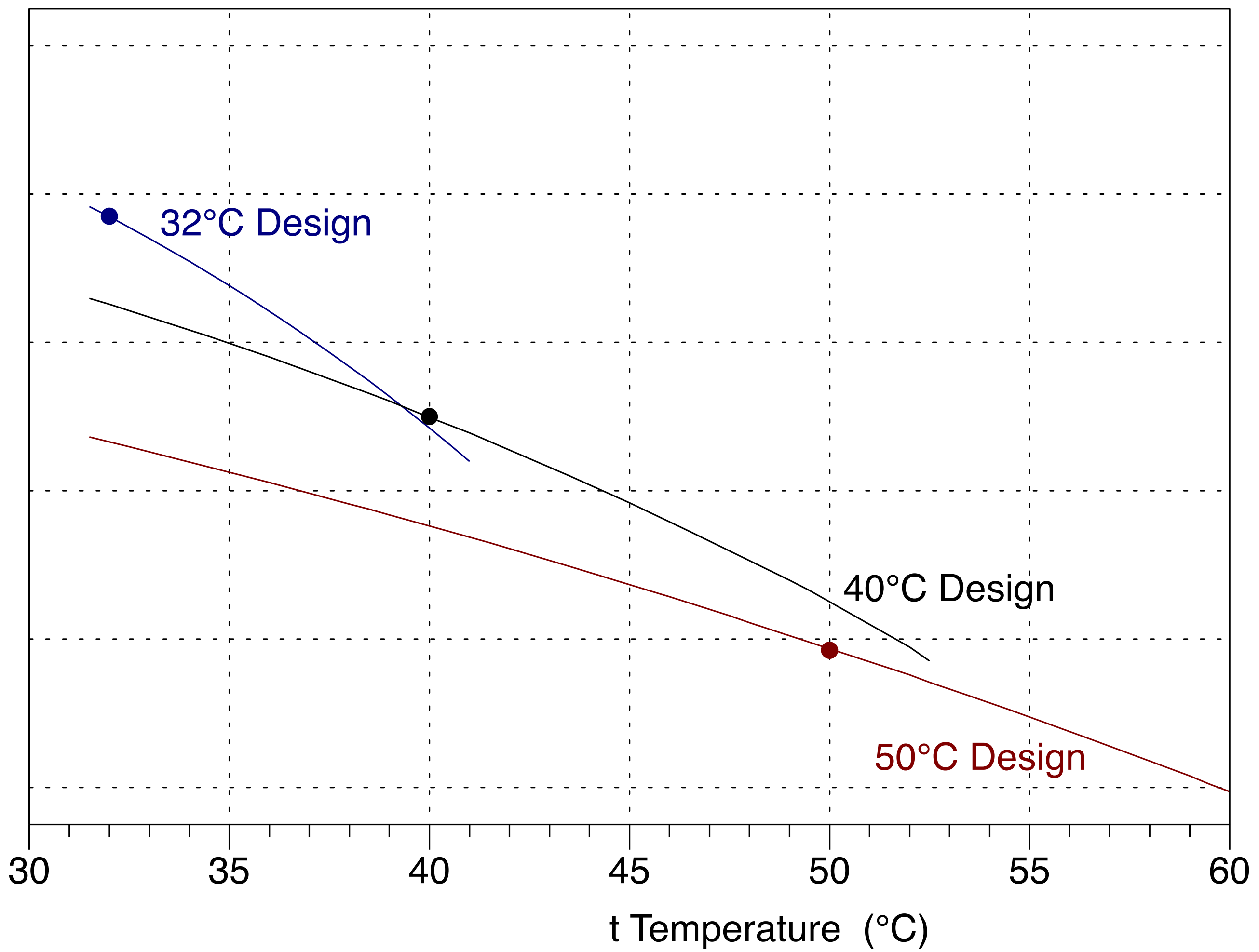
Maximum Off-Design Efficiency at Rated Power Output

25 MPa High-Pressure Limit

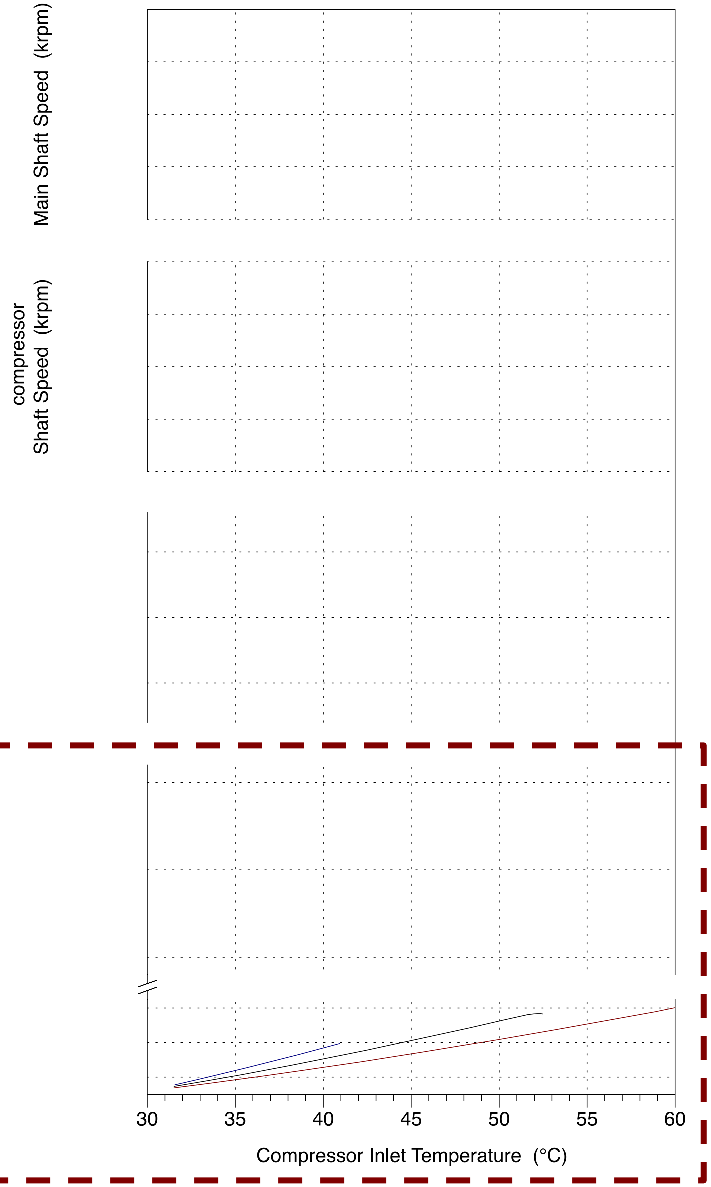


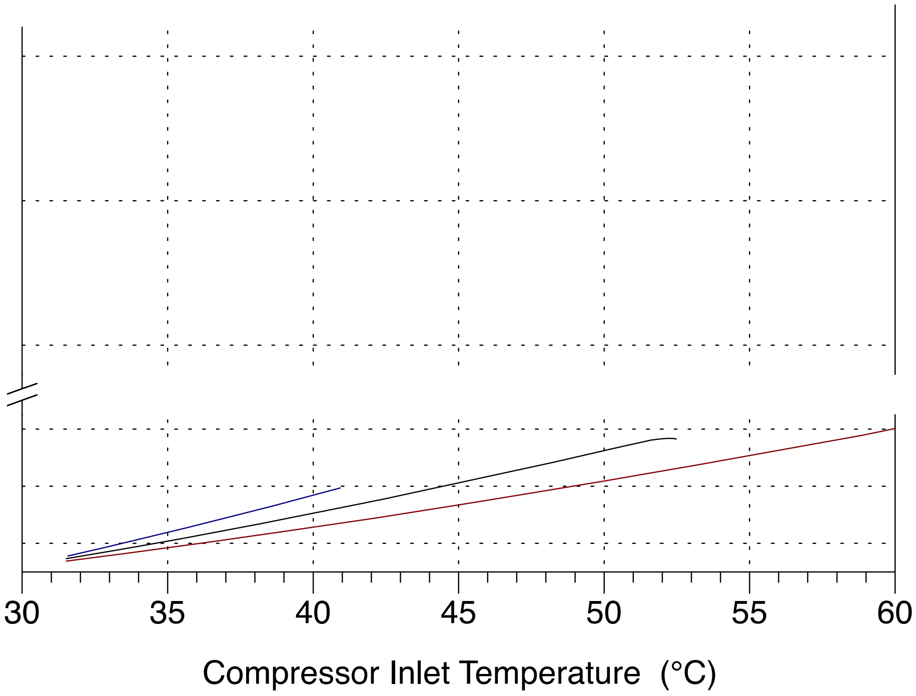
Maximum Off-Design Efficiency at Rated Power Output

30 MPa High-Pressure Limit

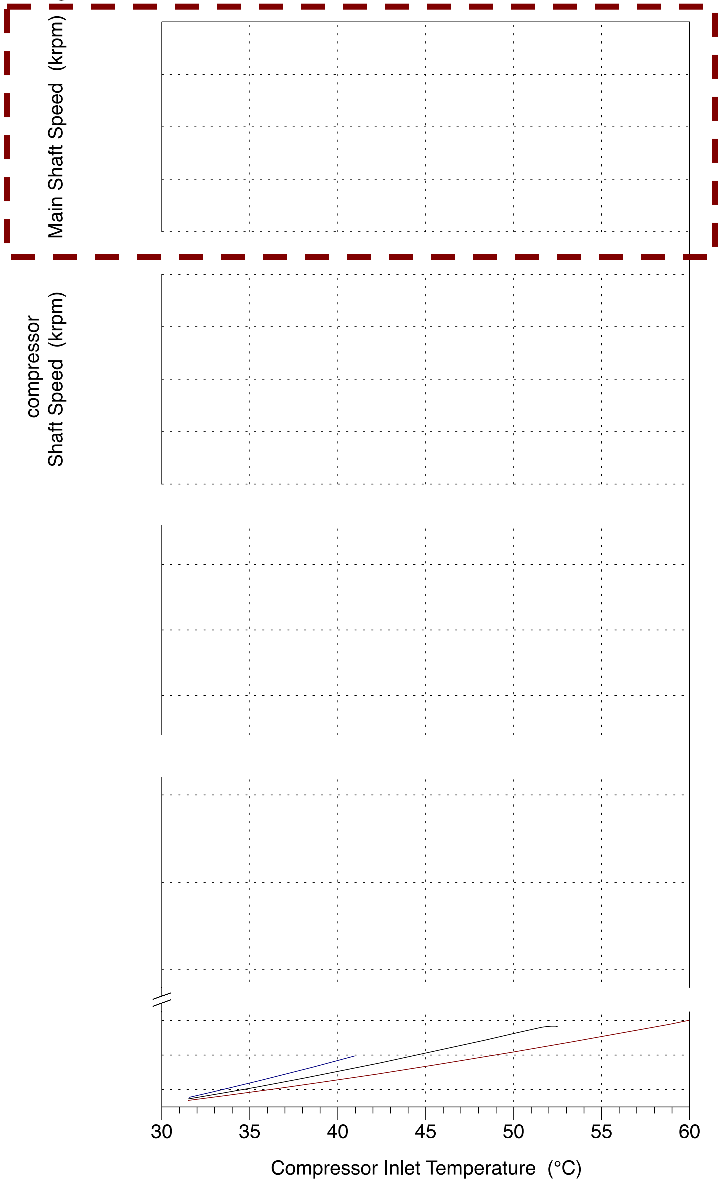


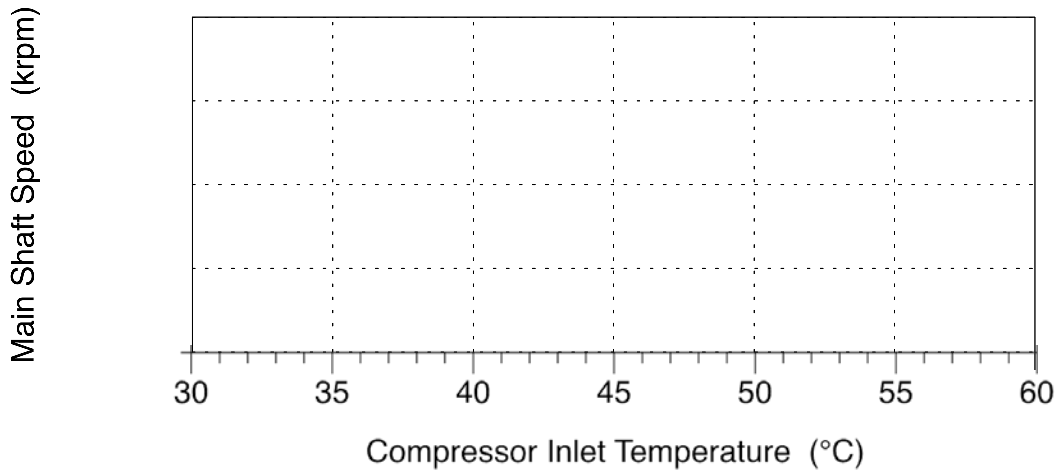
Corresponding Control Parameters



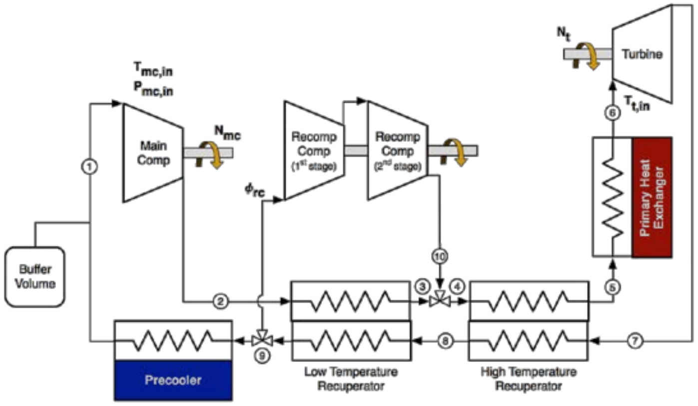


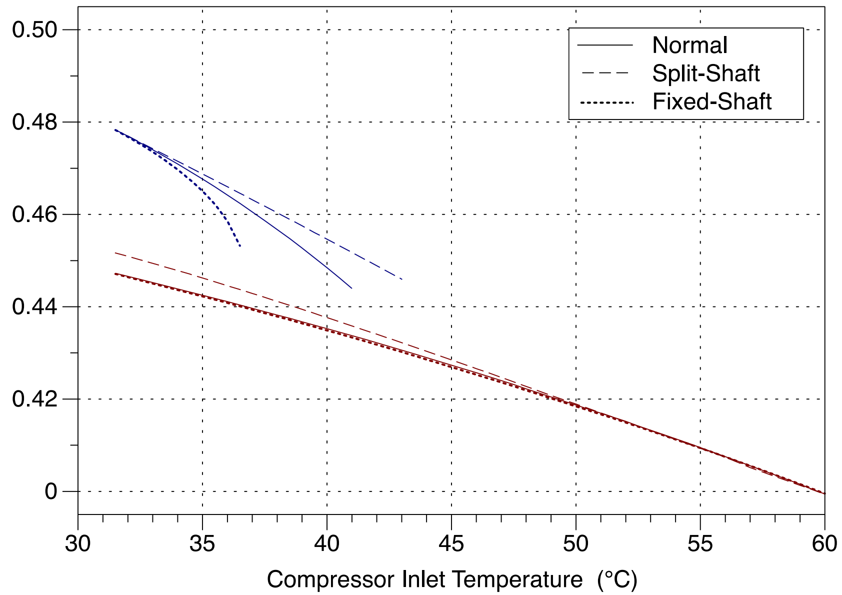
Corresponding Control Parameters

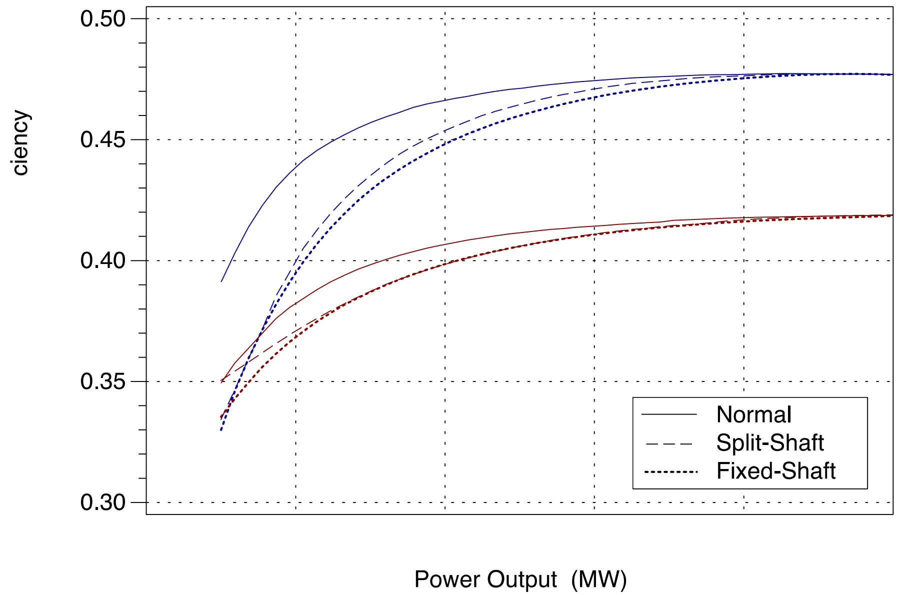




Investigating Shaft Configurations







- Normal – single shaft, variable speed (identical to previous results)
- Split-Shaft – variable speed compressor, turbine fixed at 3,600 rpm
- Fixed-Shaft – single shaft, fixed at design-point speed

(Recompressor is always driven by a variable speed motor)

Conclusions

- A flexible and computationally efficient modeling framework was created that is appropriate for recompression and simple cycle configurations.
- Source code is well-documented and available online.
  - http://sel.me.wisc.edu/software.shtml
  - (latest off-design code will be available shortly)
- Inventory control is beneficial for maximizing off-design thermal efficiency at constant power output.
- Increasing the off-design compressor inlet temperature requires an increase in the low-side pressure of the cycle.
  - The high-pressure limit of the equipment must be considered.
- A low-temperature design has a smaller off-design operating envelope (at rated power) than a high-temperature design.

Thank You