Solar Energy Laboratory

NEUP Nuclear Energy University Program

U.S. Department of Energy

THE UNIVERSITY of WISCONSIN MADISON

Supercritical Brayton Power Conversion with a Direct Cooled Reactor for Space Power

Presenting Author: Becky Sondelski

Collaborators: Greg Nellis, Alex Swenson, Paul Wilson, and Mark Anderson

University of Wisconsin-Madison

Thanks to: Jeff Breedlove and Tom Conboy – Creare

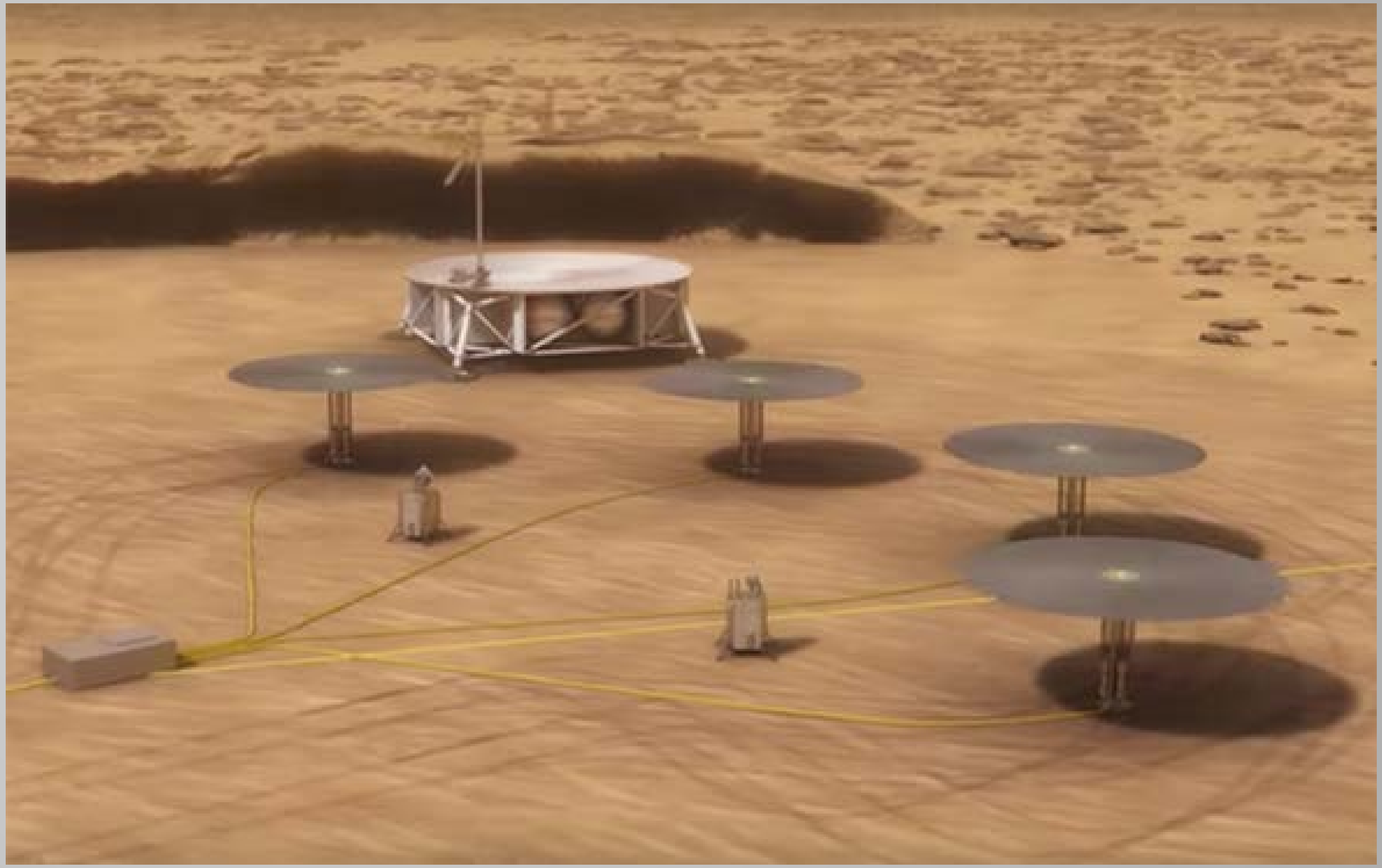
Matt Carlson – Sandia National Laboratory

Funding: DOE Nuclear Energy University Program Award Number DE-NE0008679

Creare WISCO2 CNERG Computational Nuclear Engineering Research Group Sandia National Laboratories

Surface Power for Human Exploration

- Astronauts' habitat
- Oxygen
- Water
- Propellant
- Science equipment

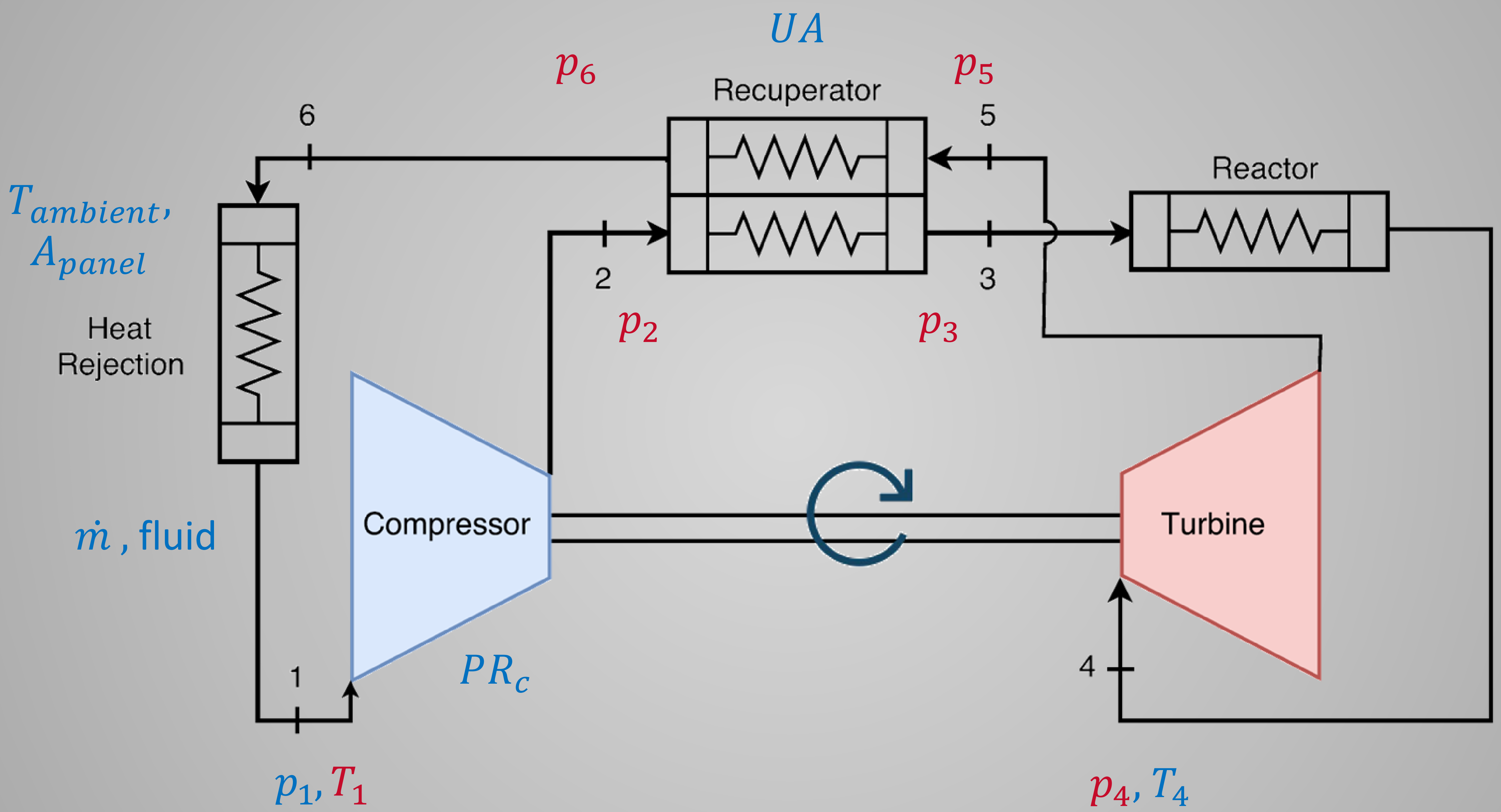


Credit: NASA

Project Goals

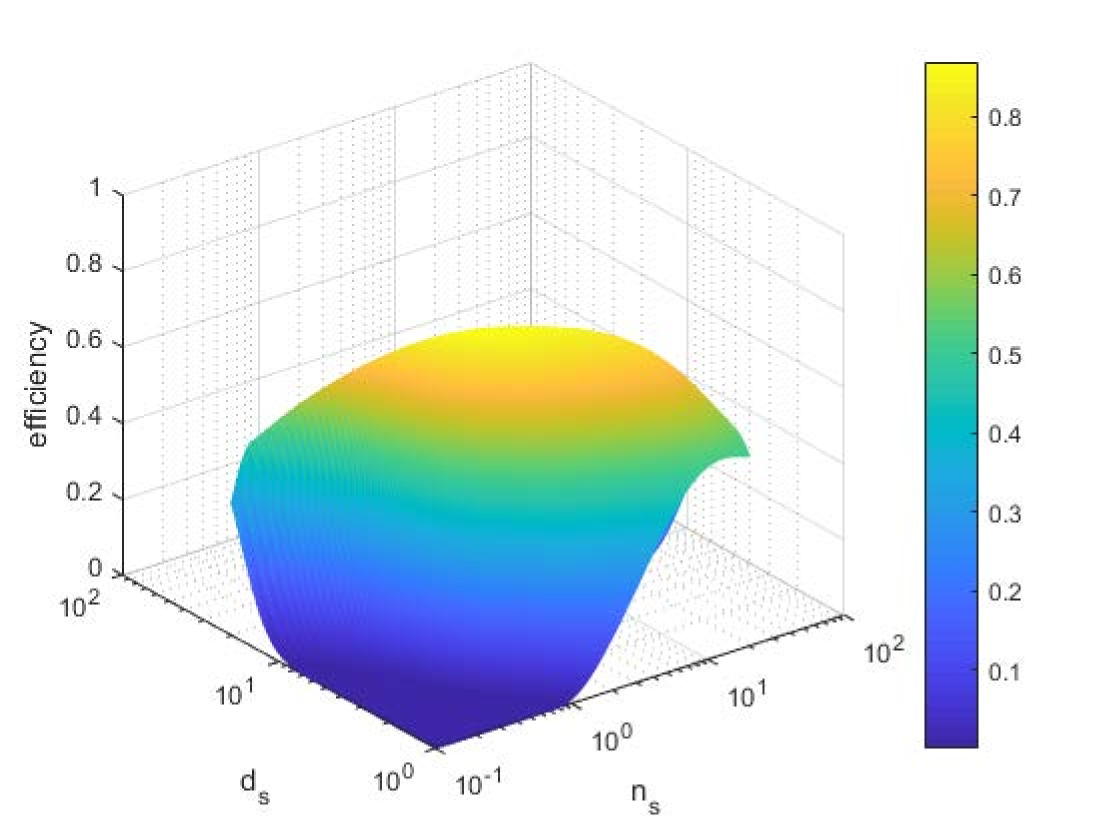
- Model and integrate Brayton cycle components
  - Compressor
  - Turbine
  - Recuperator
  - Radiator
- Optimize cycle for lowest mass
  - Radiator
  - Recuperator
  - Reactor
- Parametric studies

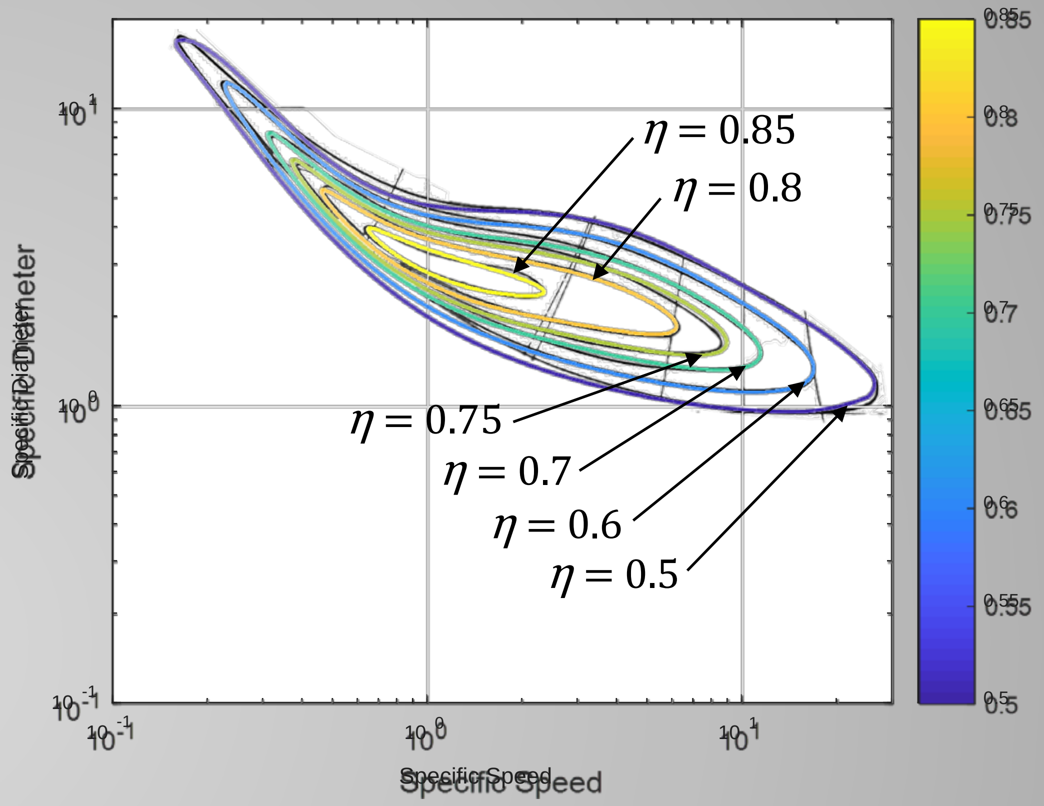
Cycle Model



UA
p_6
p_5
Recuperator
6
5
Reactor
$T_{ambient}$,
A_{panel}
2
3
p_2
p_3
Heat Rejection
Compressor
Turbine
$\dot{m}$, fluid
PR_c
1
4
p_1, T_1
p_4, T_4

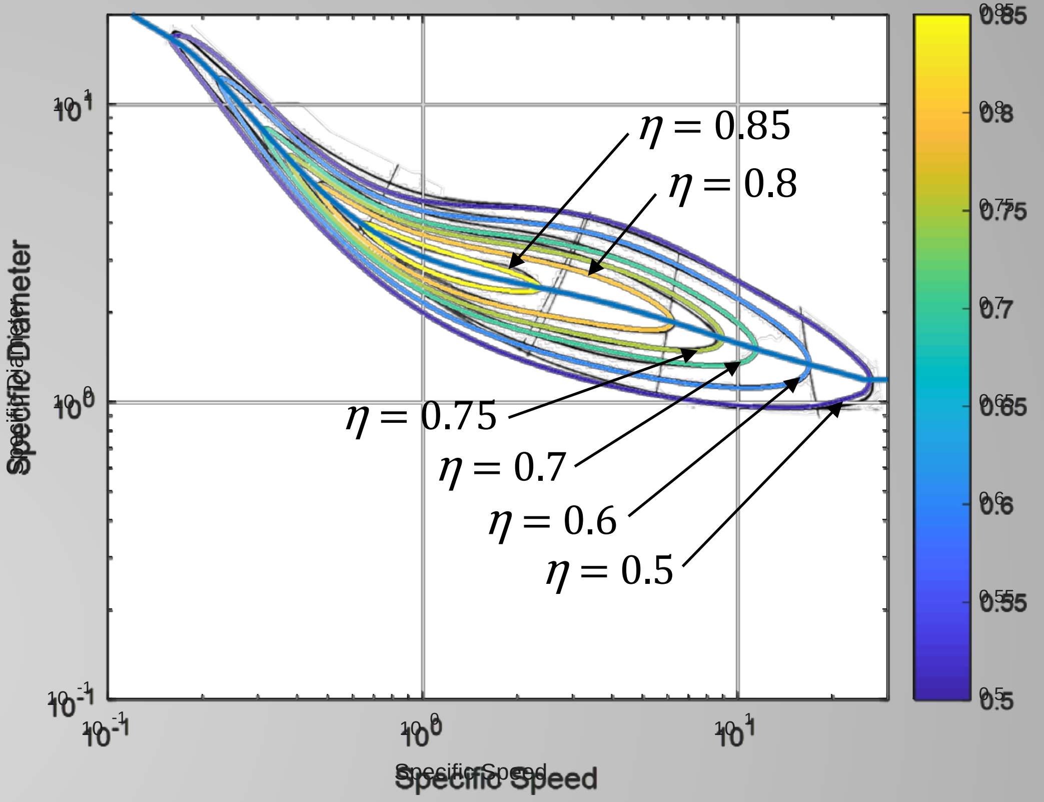
Compressor Model

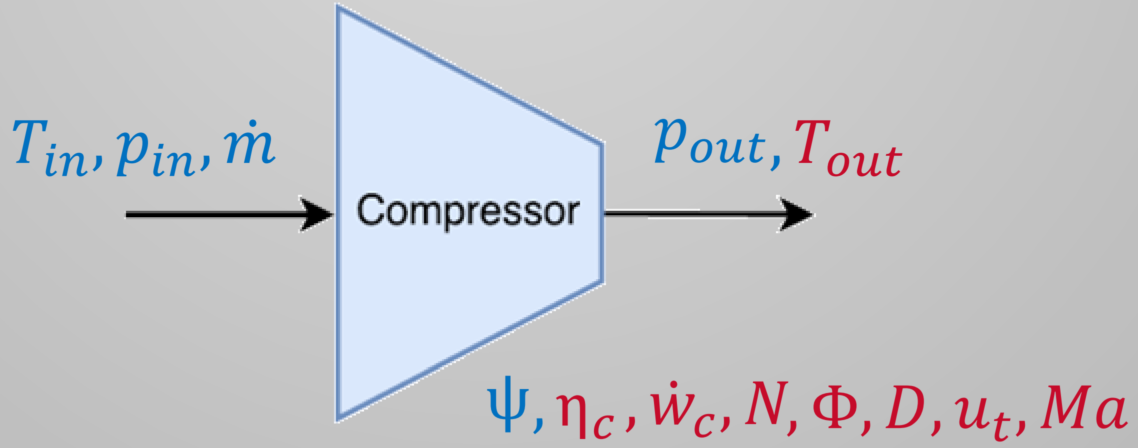


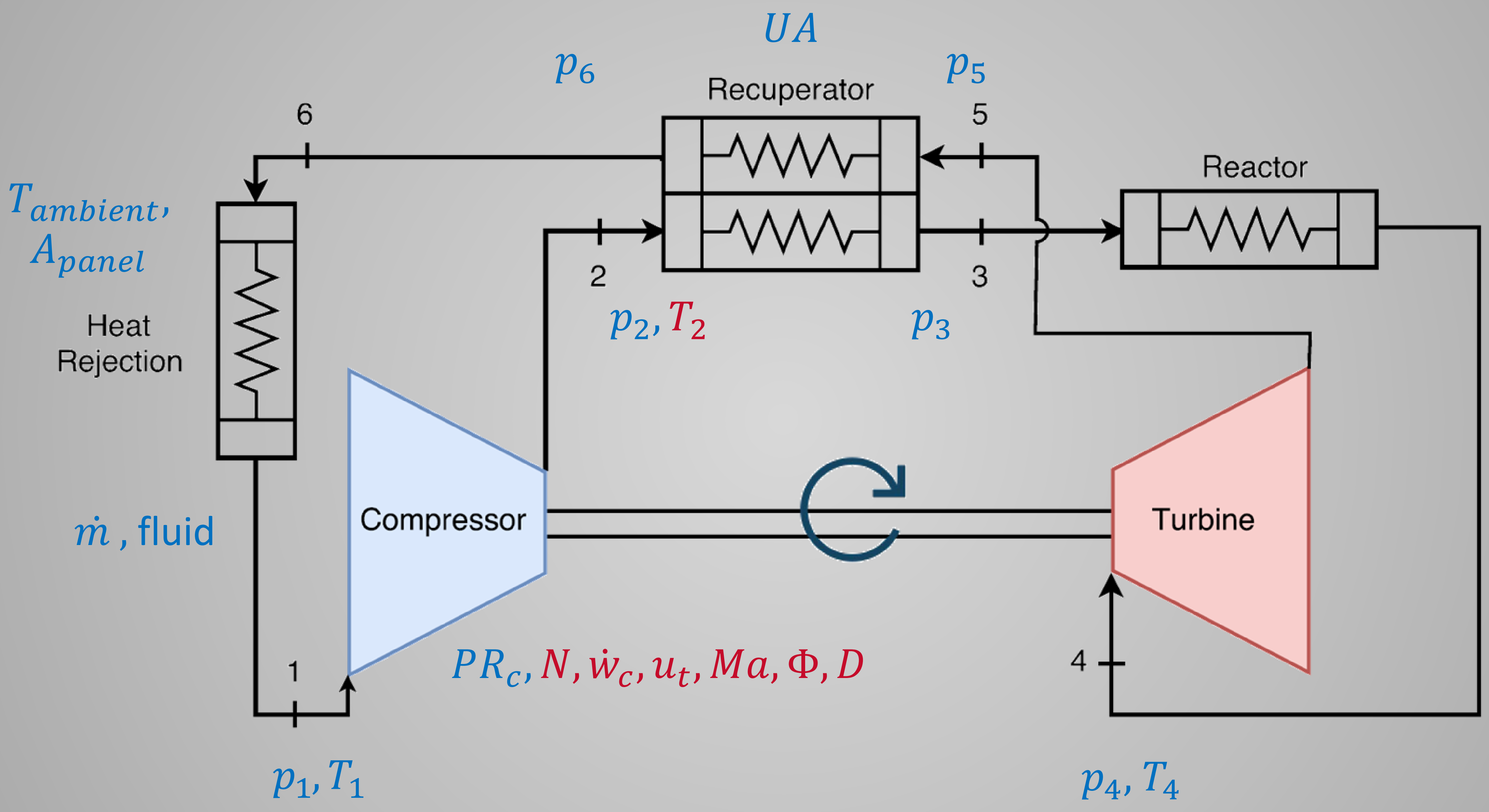


Compressor Model

1. Set head coefficient
2. Peak line of Balje Contours
3. Specific speed, diameter, efficiency
4. Isentropic enthalpy change
5. Power, shaft speed, and outlet temperature

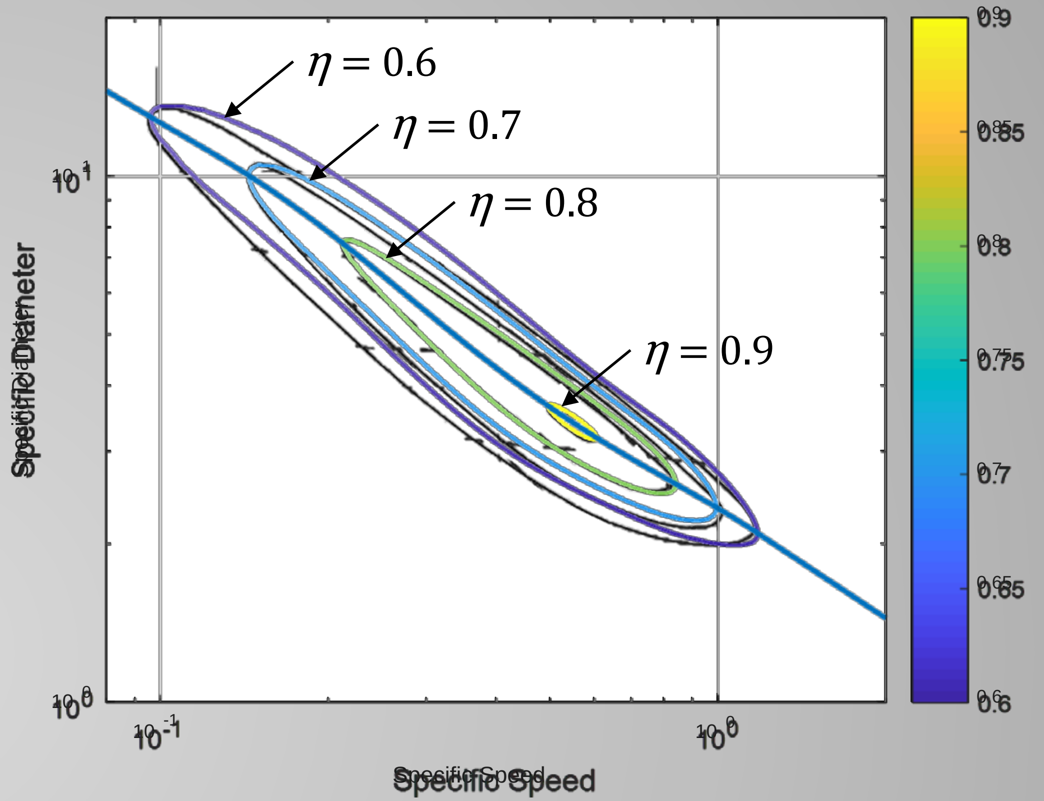


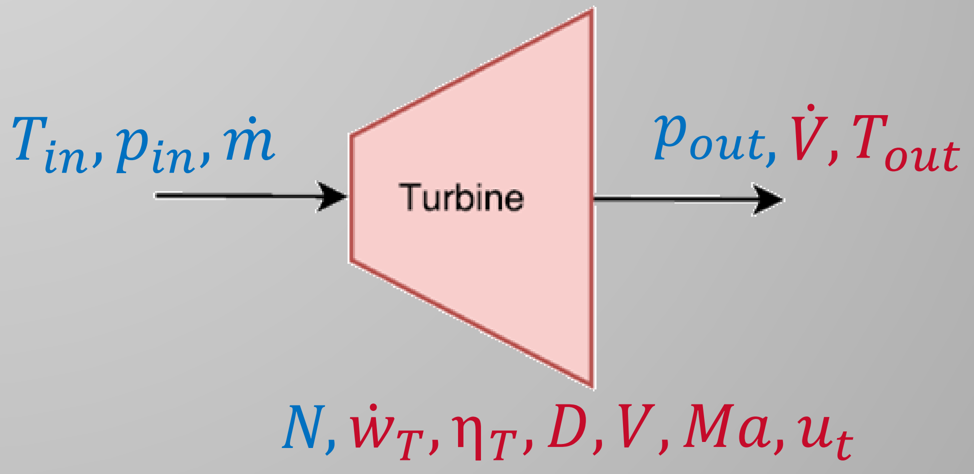


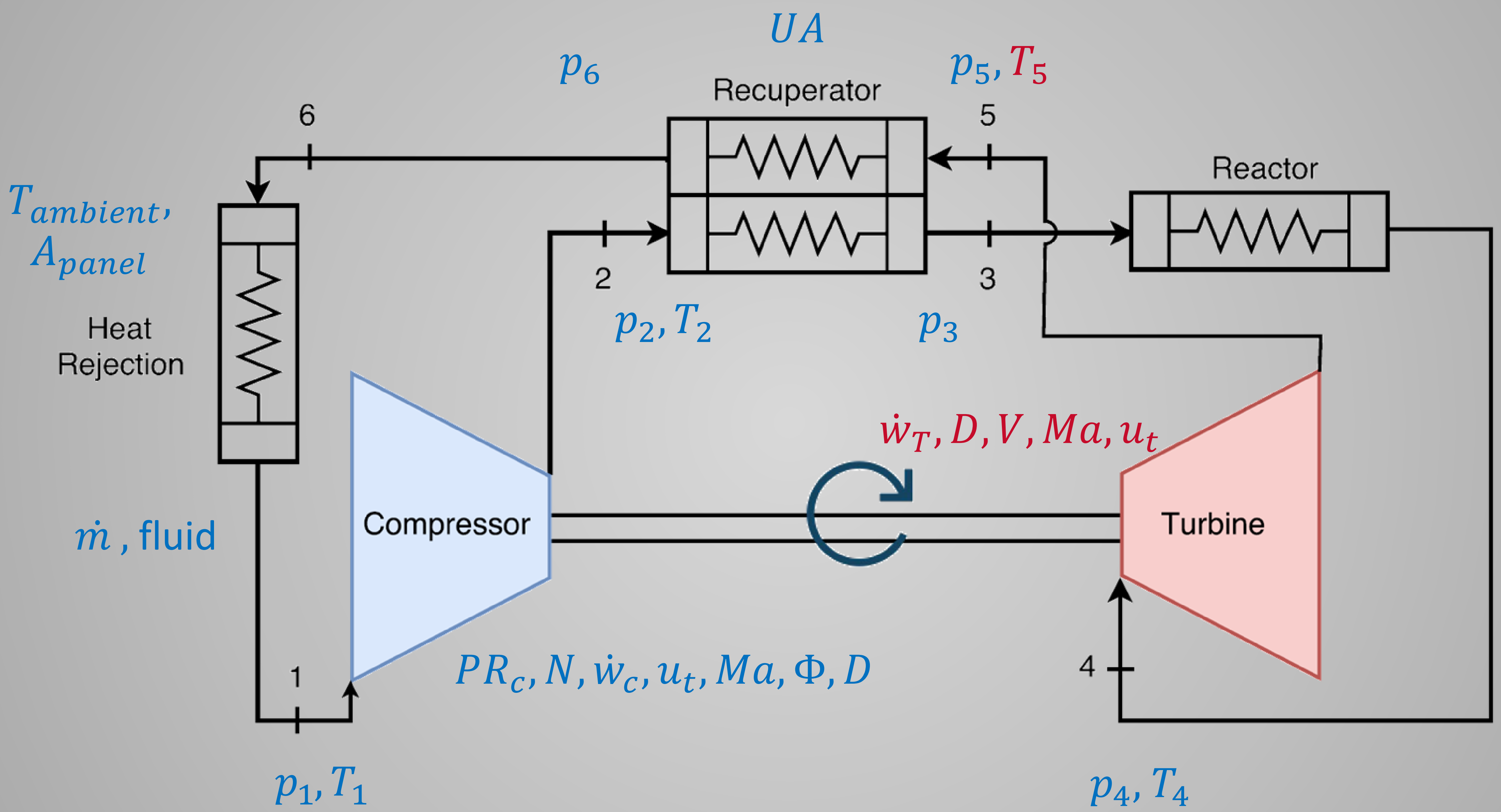

UA
p_6
p_5
Recuperator
6
5
Reactor
$T_{ambient}$,
A_{panel}
2
3
Heat
Rejection
p_2, T_2
p_3
Compressor
Turbine
$\dot{m}$, fluid
1
4
$PR_c, N, \dot{w}_c, u_t, Ma, \Phi, D$
p_1, T_1
p_4, T_4

Turbine Model

1. Curve fit Balje Contours
2. Guess outlet volumetric flow rate
3. Isentropic enthalpy change
4. Find efficiency and get power output and outlet temperature
5. Check volumetric flow rate convergence criteria



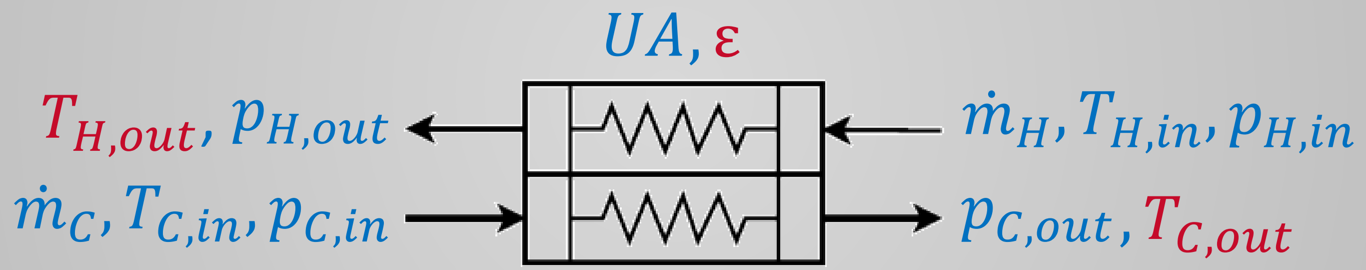


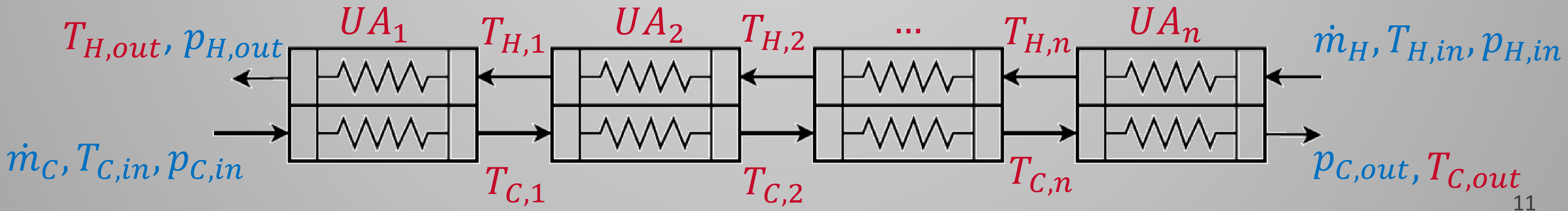


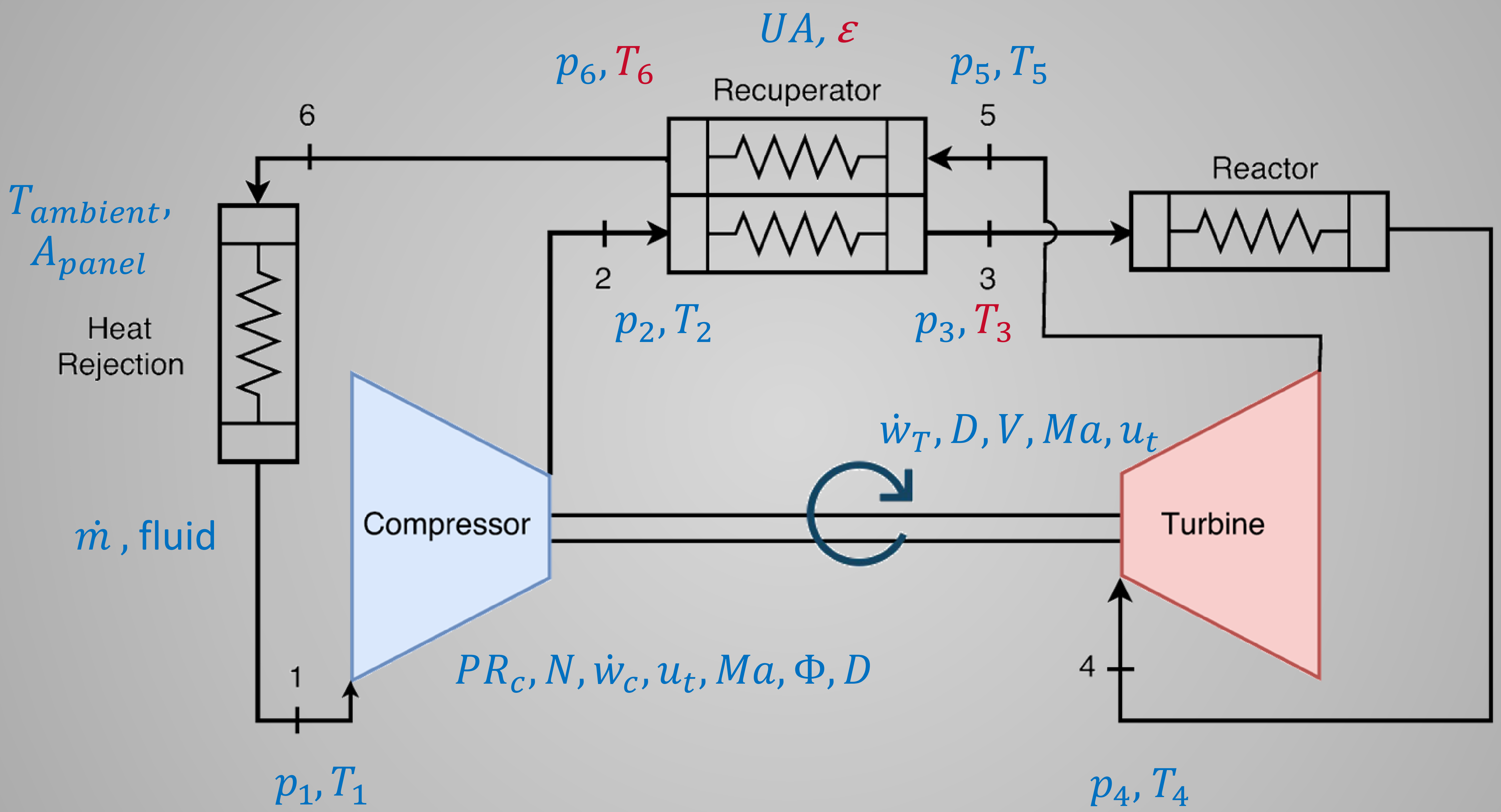
UA
p_6
Recuperator
p_5, T_5
6
5
Reactor
$T_{ambient}, A_{panel}$
2
3
Heat Rejection
p_2, T_2
p_3
$\dot{w}_T, D, V, Ma, u_t$
Compressor
Turbine
$\dot{m}$, fluid
4
1
$PR_c, N, \dot{w}_c, u_t, Ma, \Phi, D$
p_1, T_1
p_4, T_4

Recuperator Model

1. Guess $T_{H,out}$
2. Calculate overall heat transfer
3. Split evenly to solve for temperatures
4. Use ε-NTU to solve for conductance
5. Compare with overall UA
6. Check UA convergence criteria

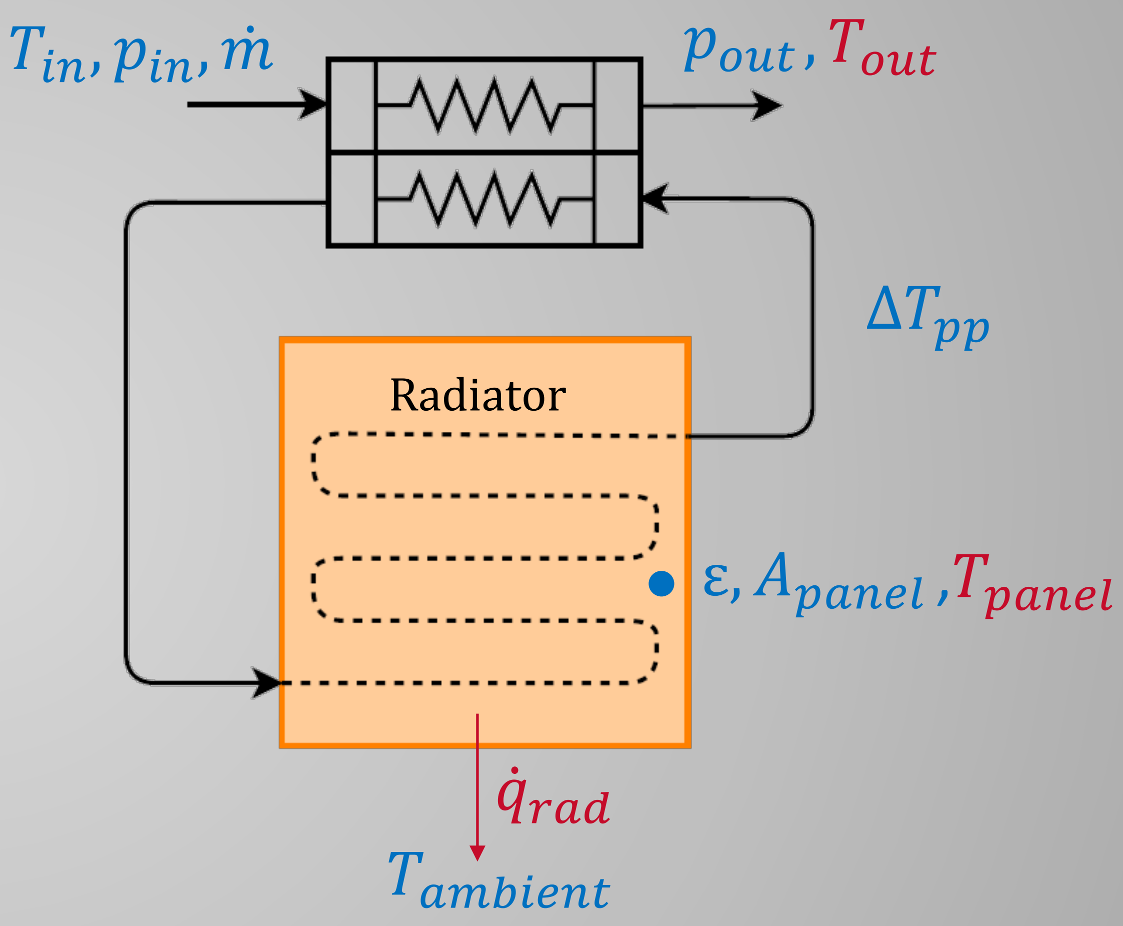


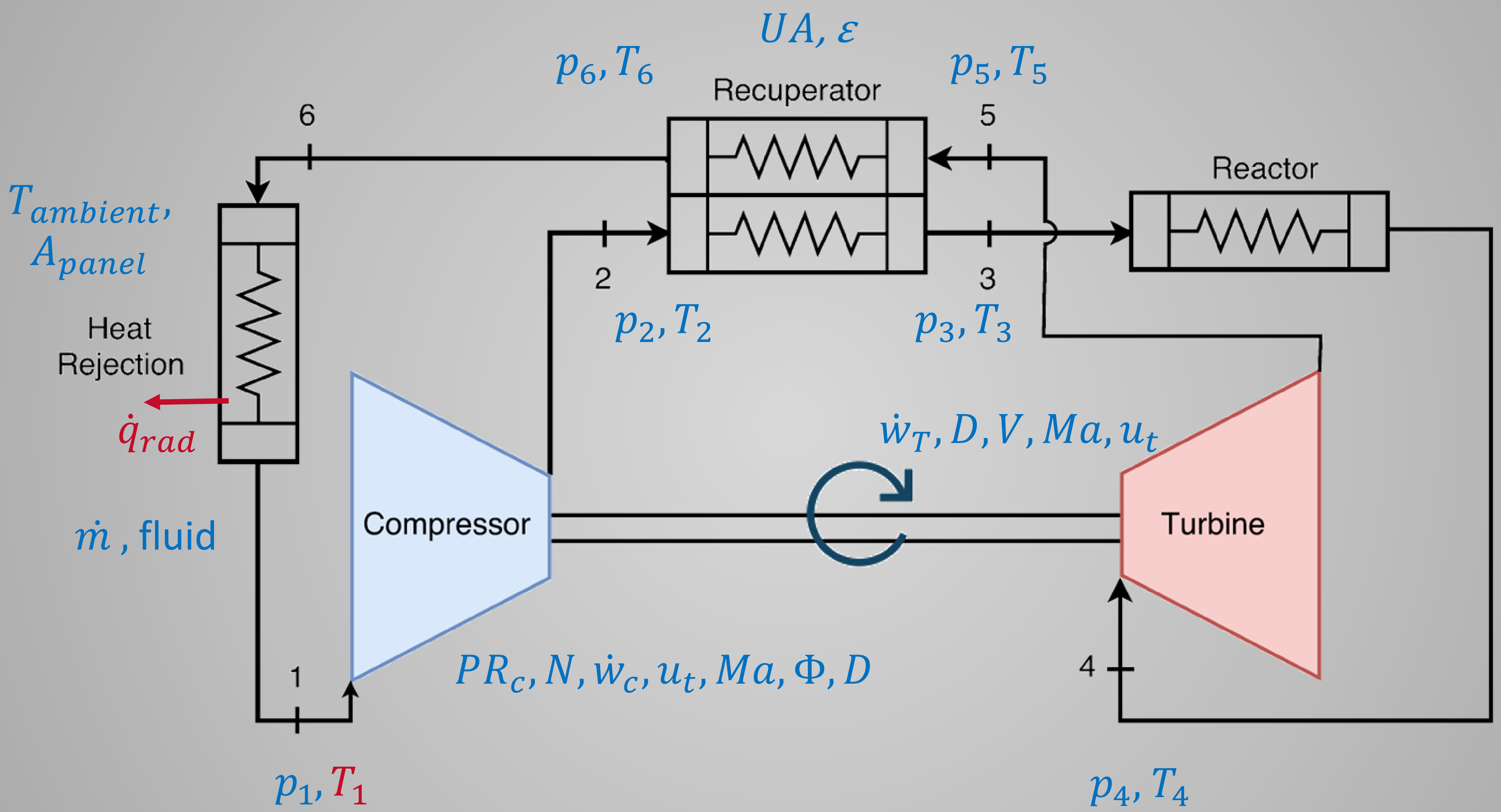



UA, ε
p_6, T_6
Recuperator
p_5, T_5
6
5
Reactor
$T_{ambient}$,
A_{panel}
2
3
Heat
Rejection
p_2, T_2
p_3, T_3
$\dot{w}_T, D, V, Ma, u_t$
$\dot{m}$, fluid
Compressor
Turbine
$PR_c, N, \dot{w}_c, u_t, Ma, \Phi, D$
1
4
p_1, T_1
p_4, T_4

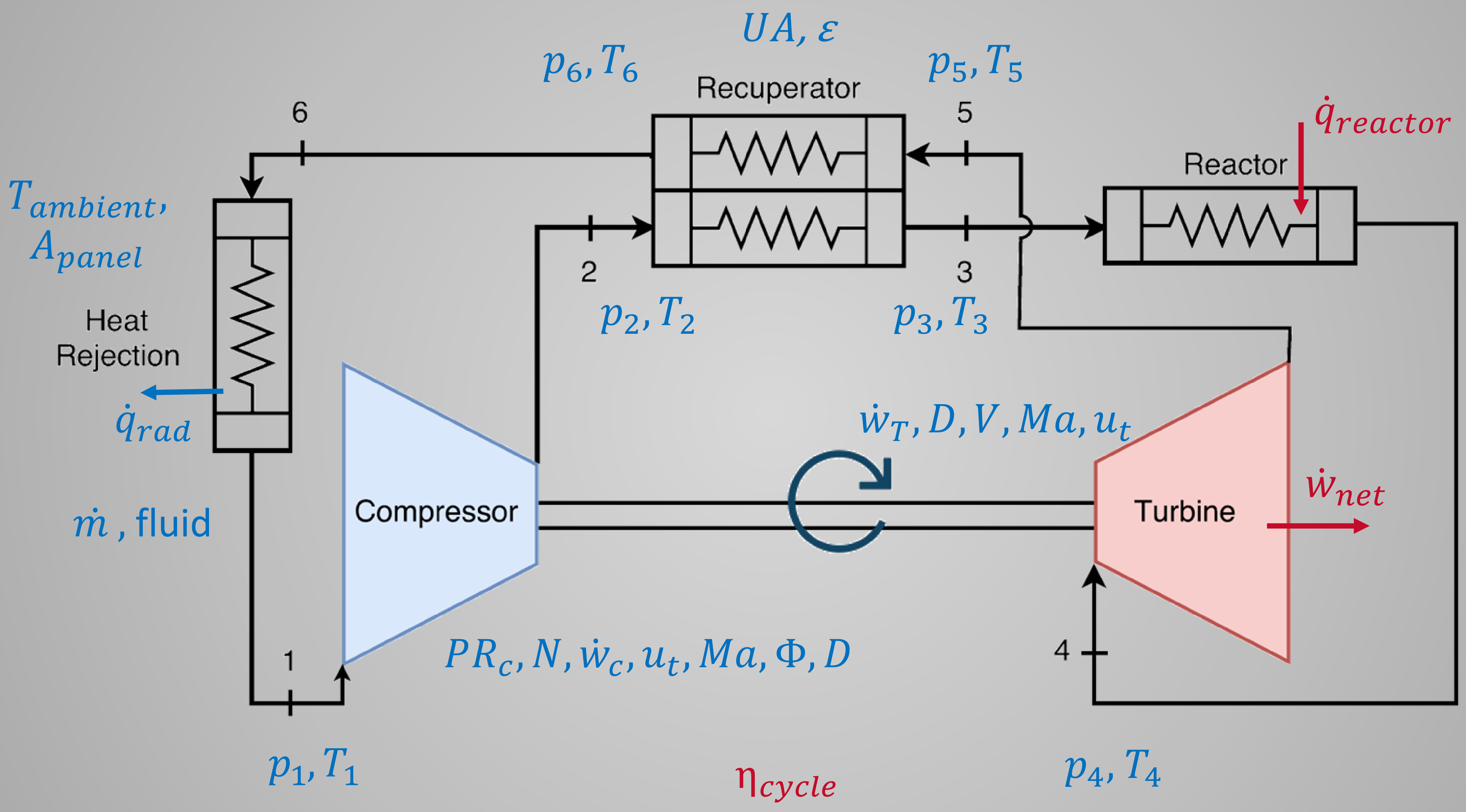
Radiator Model

1. Guess T_{out}
2. Radiator heat output
3. Panel temperature
4. Outlet temperature
5. Check T_{out} convergence criteria





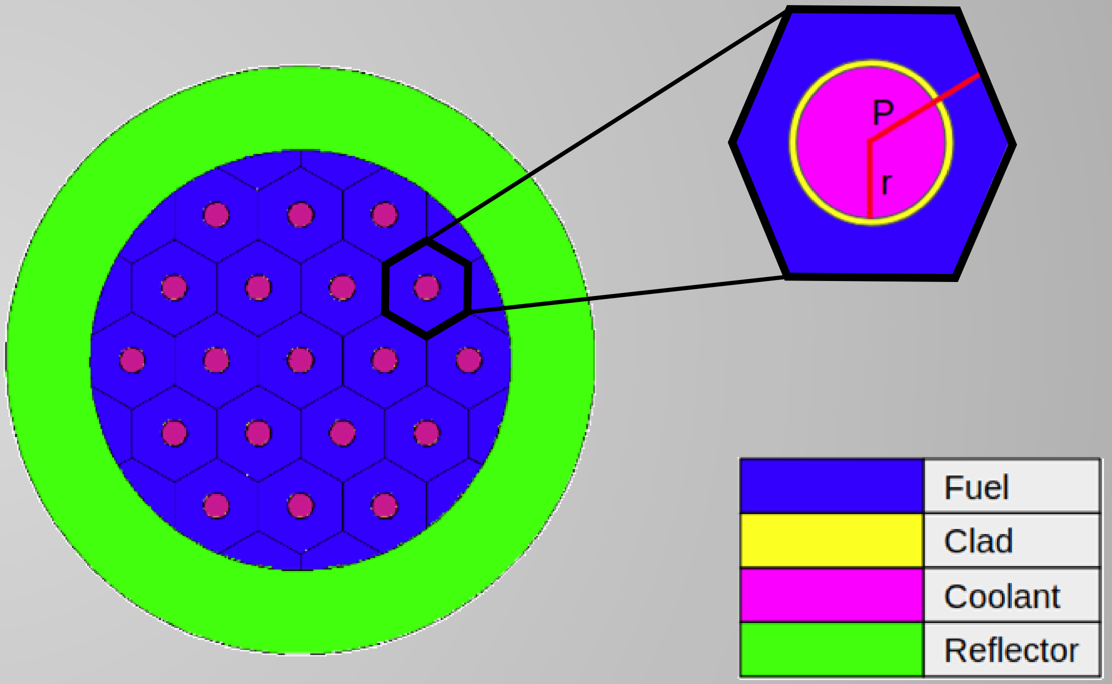
Check T_1 convergence criteria



UA, ε
p6, T6
Recuperator
p5, T5
6
5
q̇reactor
Reactor
Tambient,
Apanel
2
3
p2, T2
p3, T3
Heat
Rejection
q̇rad
ẇT, D, V, Ma, ut
Compressor
Turbine
ẇnet
ṁ , fluid
PRc, N, ẇc, ut, Ma, Φ, D
1
4
p1, T1
ηcycle
p4, T4

Reactor Model

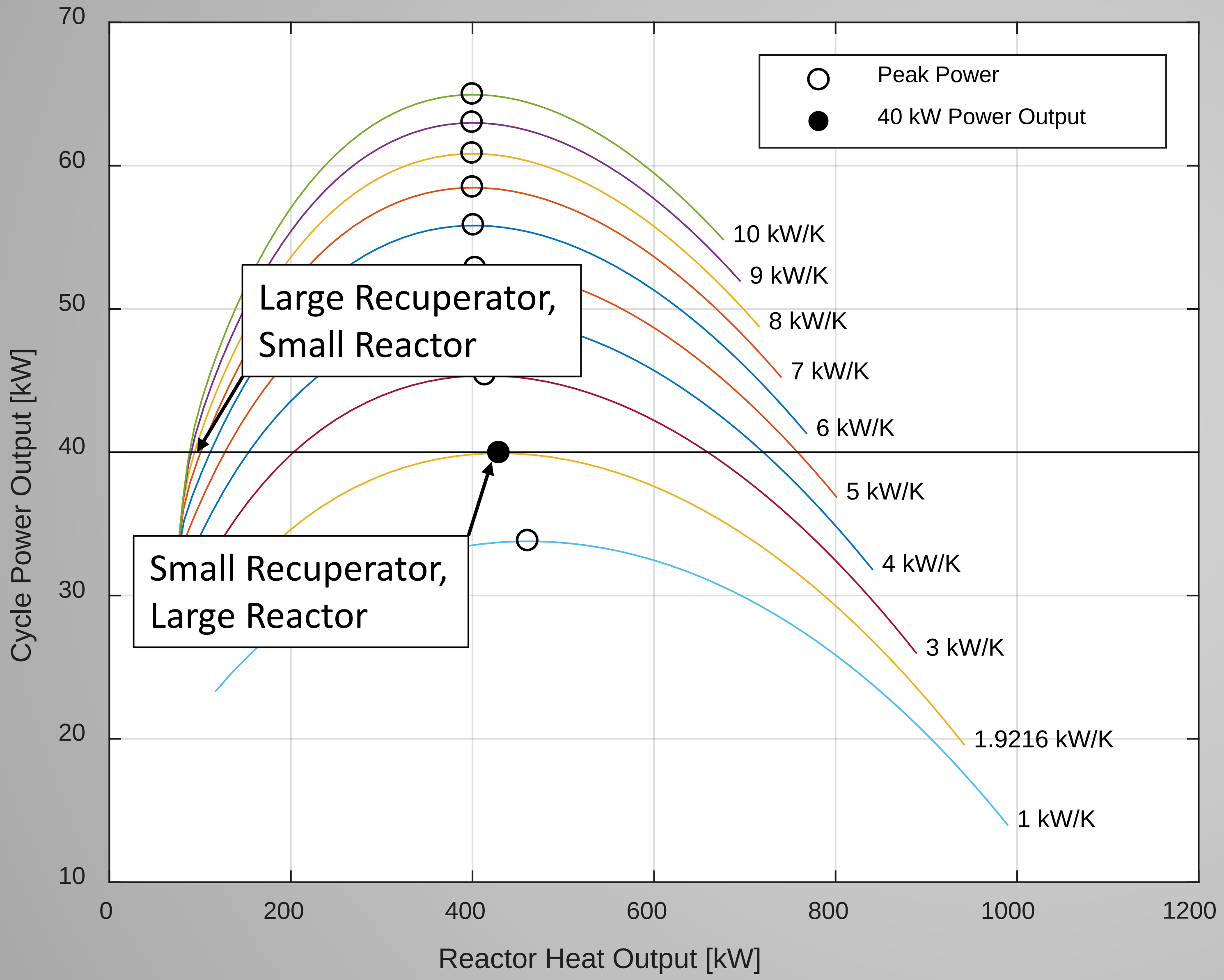
- Cermet fuel
- Thermal-hydraulics and neutronics
- Minimizes mass for given cycle parameters

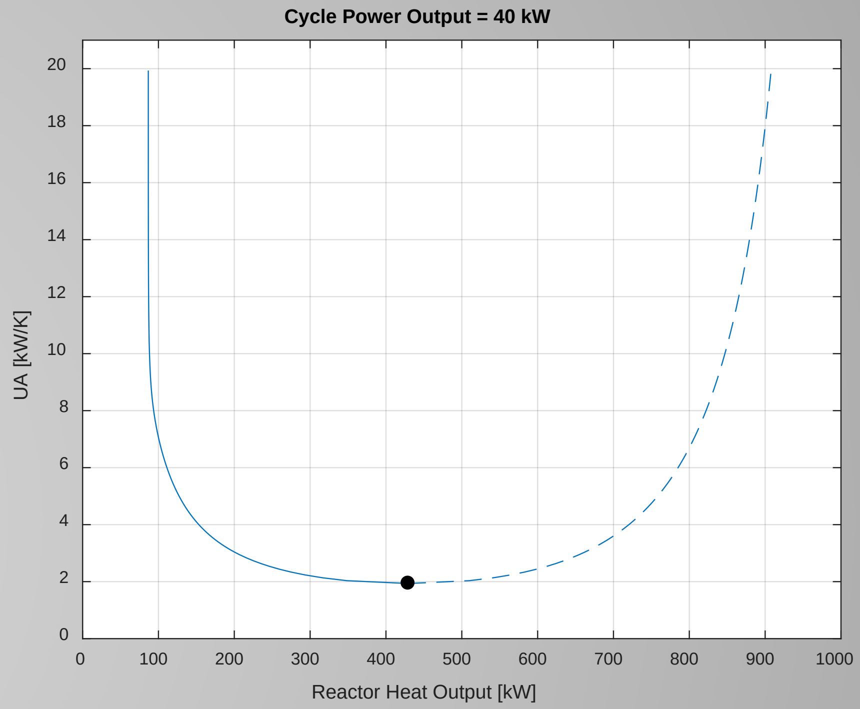


Optimization

Minimizing Mass – Reactor, Radiator, and Recuperator Tradeoffs

Reactor and Recuperator Size Tradeoffs





Cycle parameters:

- $p1 = 9{,}000$ kPa
- $T_4 = 1{,}100$ K
- $PR_c = 2$
- $T_{amb} = 100$ K
- $A_{panel} = 100\ m^2$

Fluid: supercritical CO_2

Property database: FIT

Approximate Mass Correlations

- Microtube shell and tube heat exchanger[1]

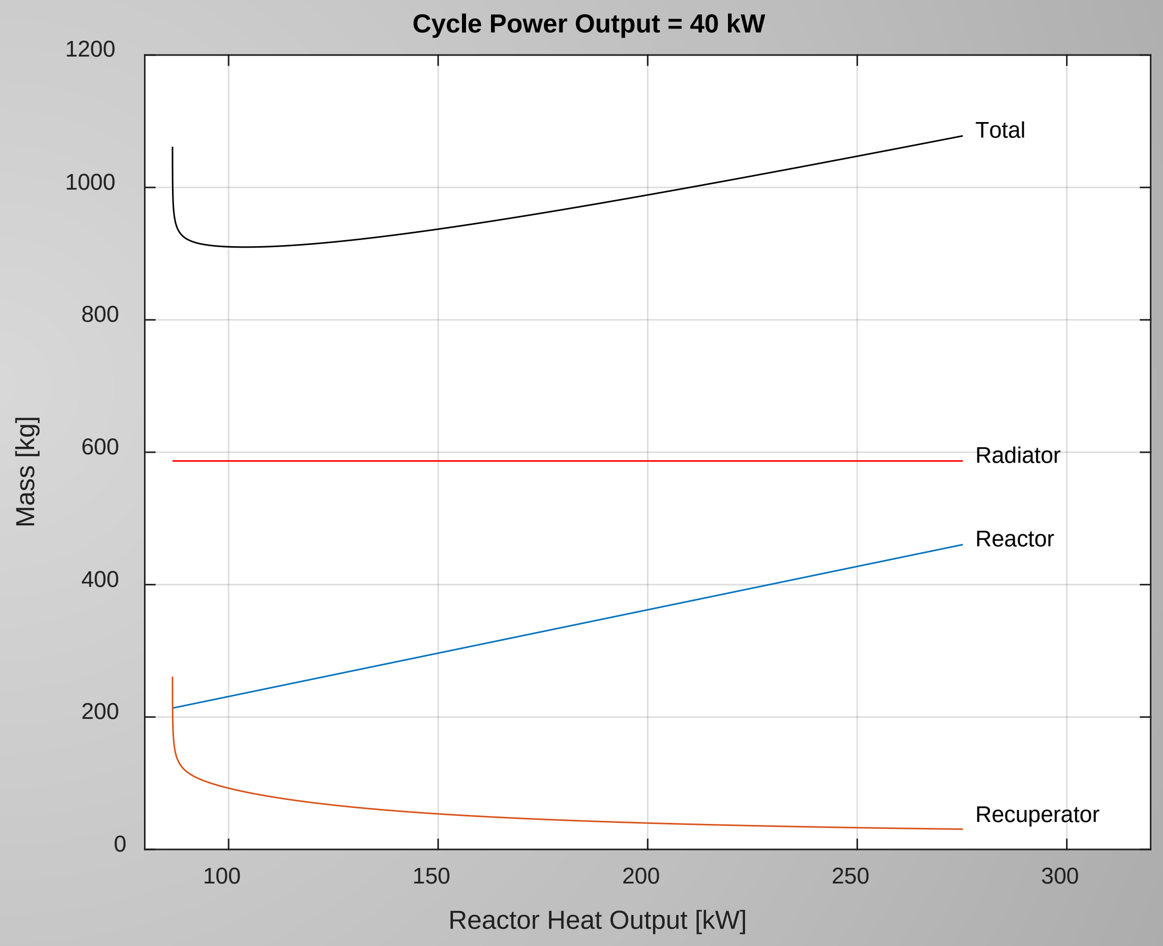
$$m_{recuperator} = 0.0131 \left[\frac{\text{kg K}}{\text{W}}\right] (UA)$$

- Gas cooled, uranium nitride fueled, pin-type reactor[2]

$$m_{reactor} = 0.00131 \left[\frac{\text{kg}}{\text{W}}\right] (q_{\text{reactor}}) + 100[\text{kg}]$$

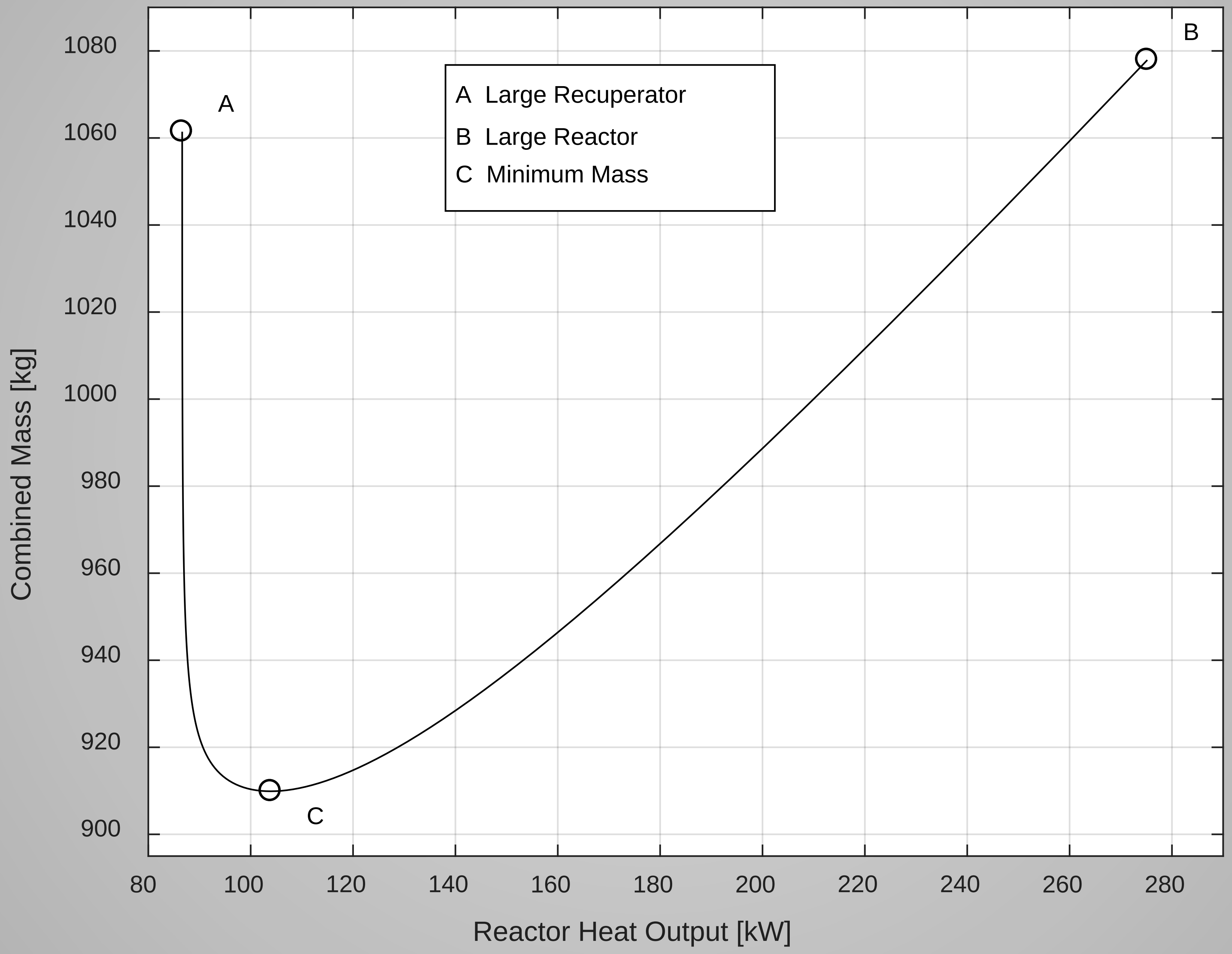
- Capillary pumped loop and conical thermal radiator[2]

$$m_{radiator} = 5.8684 \left[\frac{\text{kg}}{\text{m}^2}\right] (A_{panel})$$

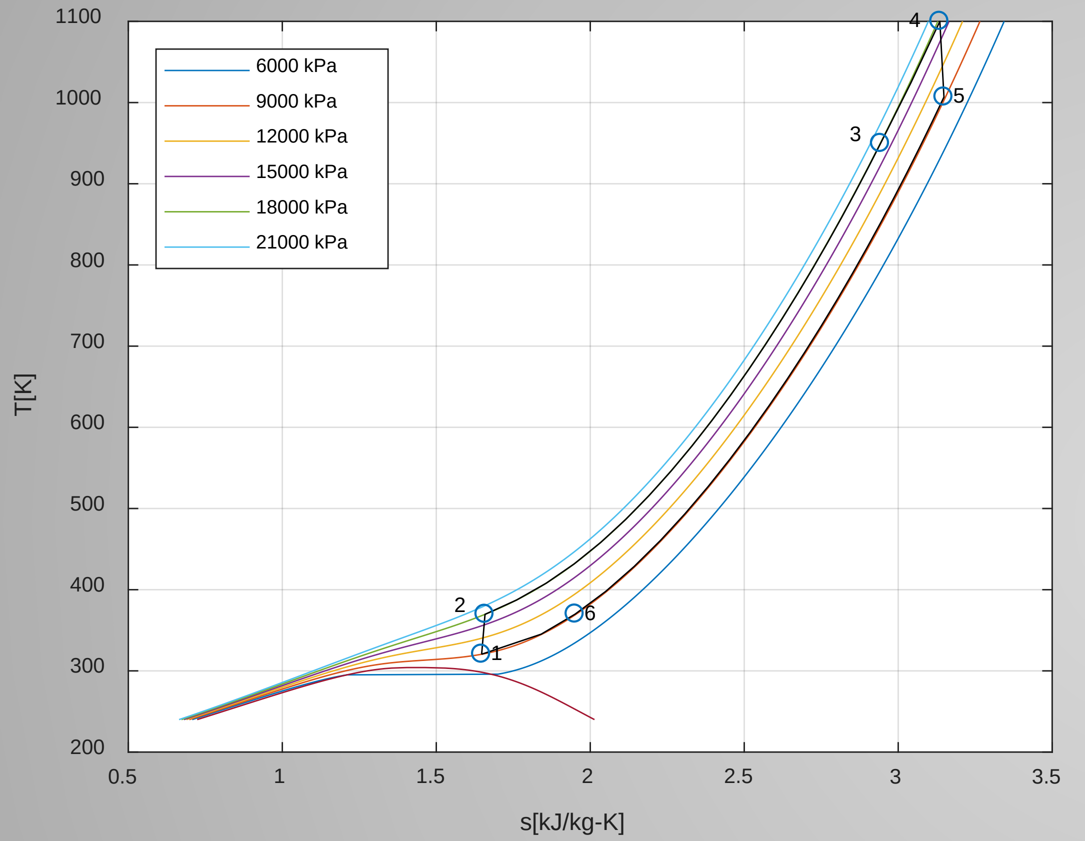


1 Breedlove et al., 2016
2 Lipinski et al., 2002

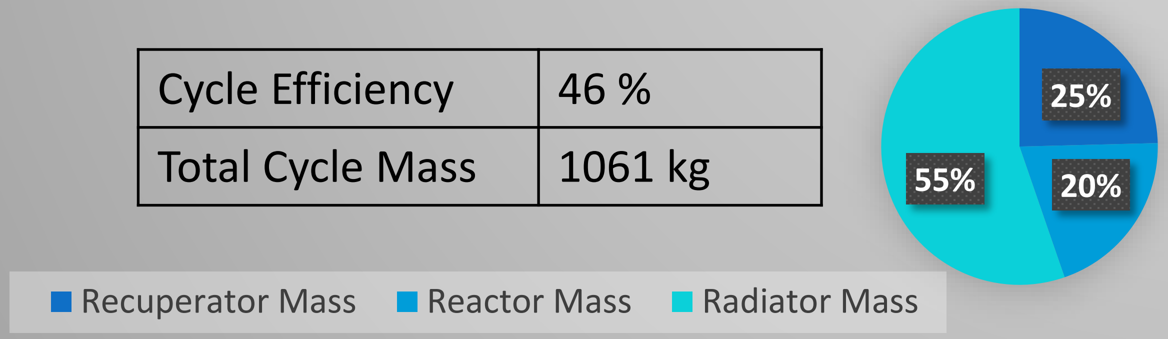
Cycle Power Output = 40 kW



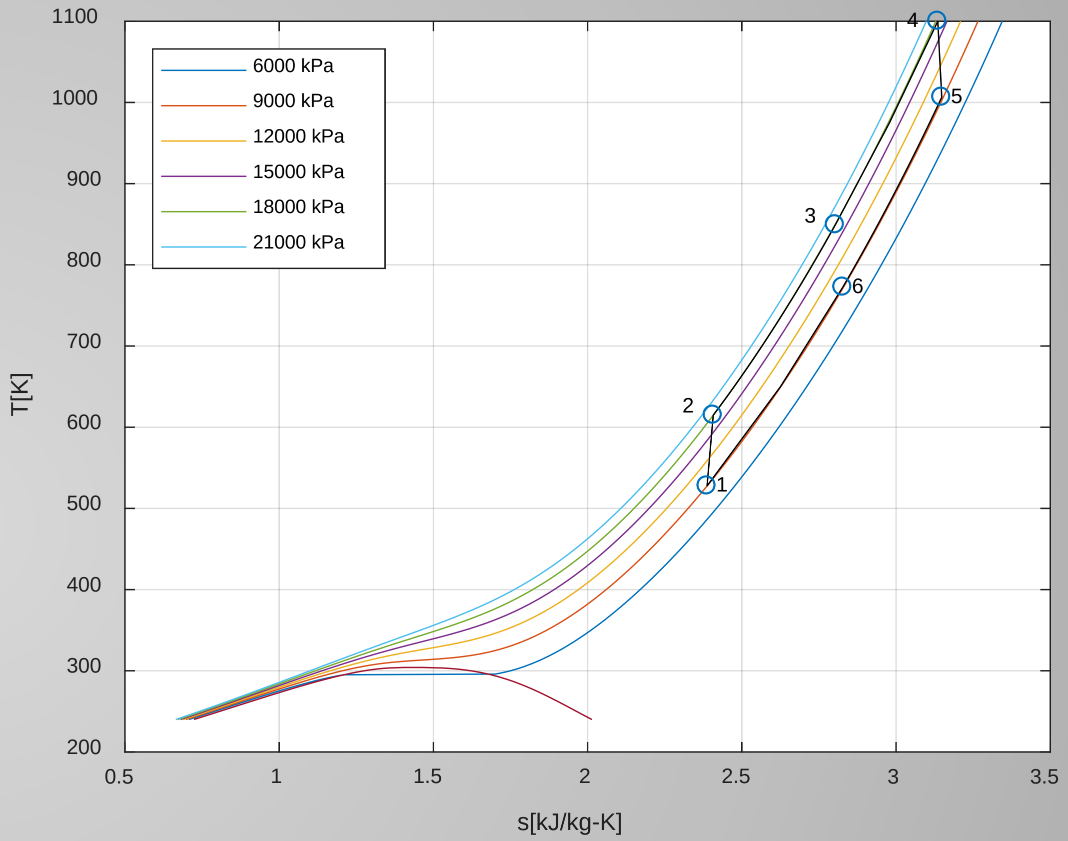
Large Recuperator



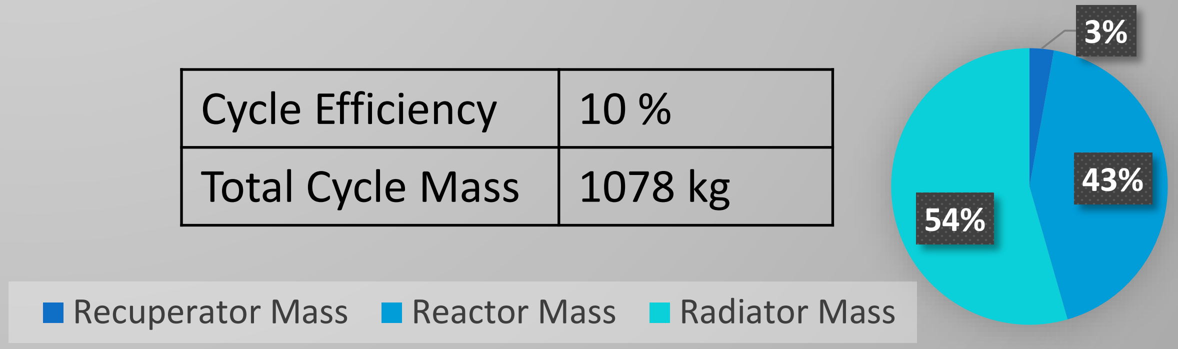
Cycle Efficiency	46 %
Total Cycle Mass	1061 kg



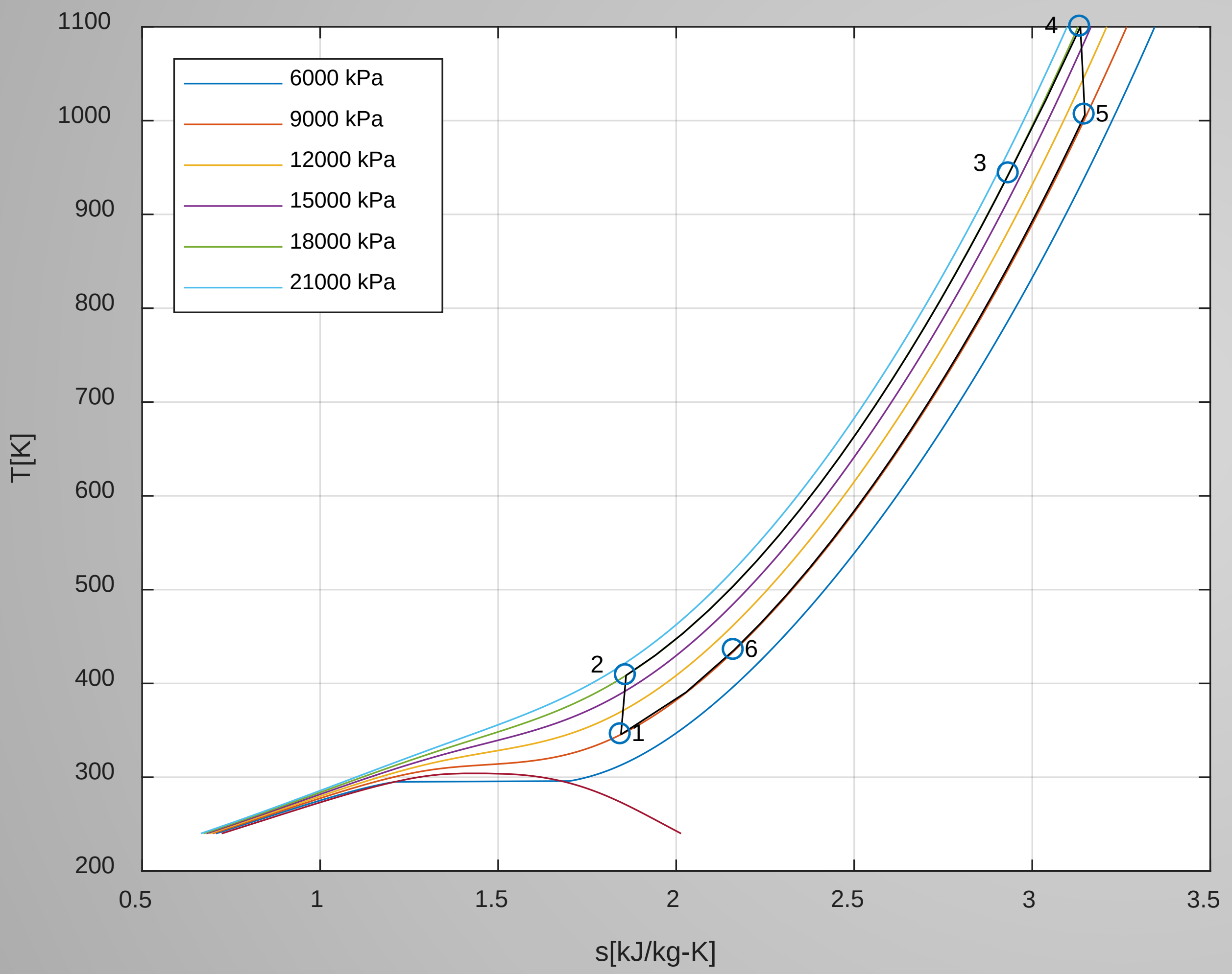
Large Reactor



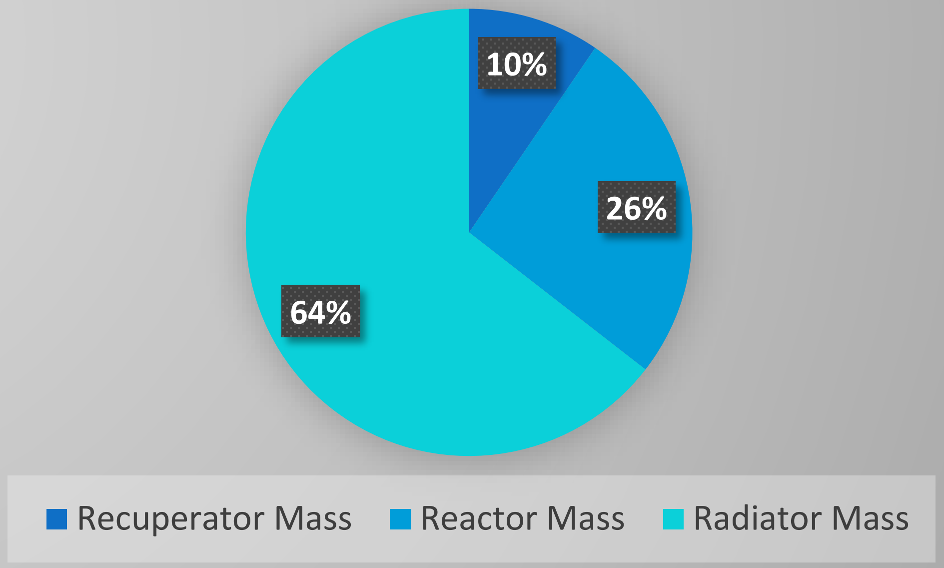
Cycle Efficiency	10 %
Total Cycle Mass	1078 kg



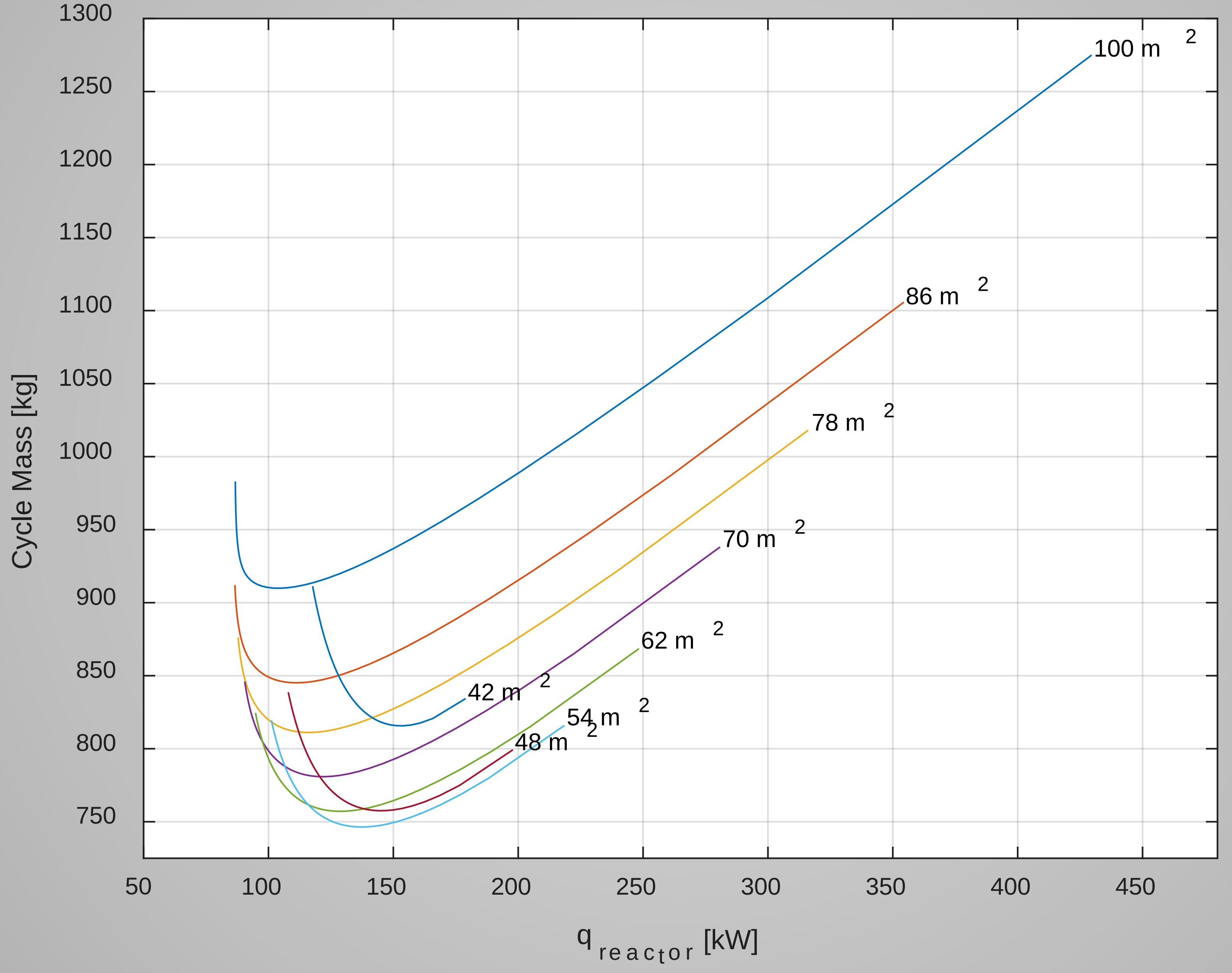
Minimum Mass Cycle



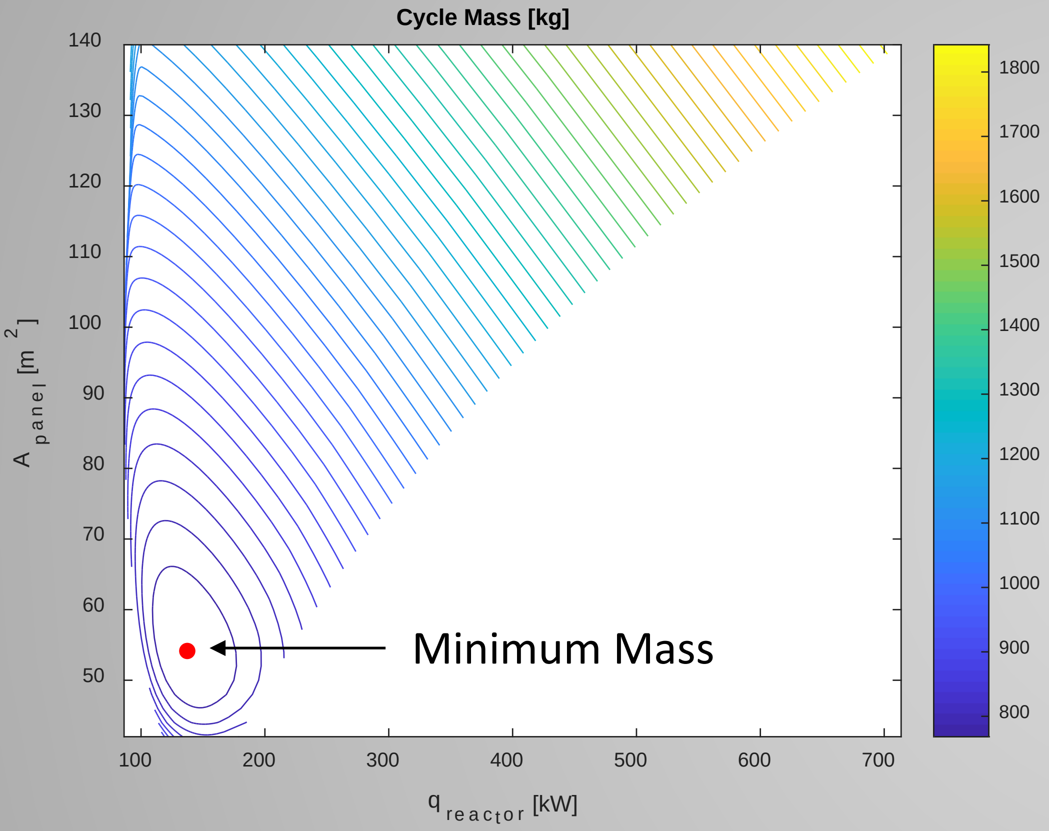
Cycle Efficiency	38 %
Total Cycle Mass	910 kg

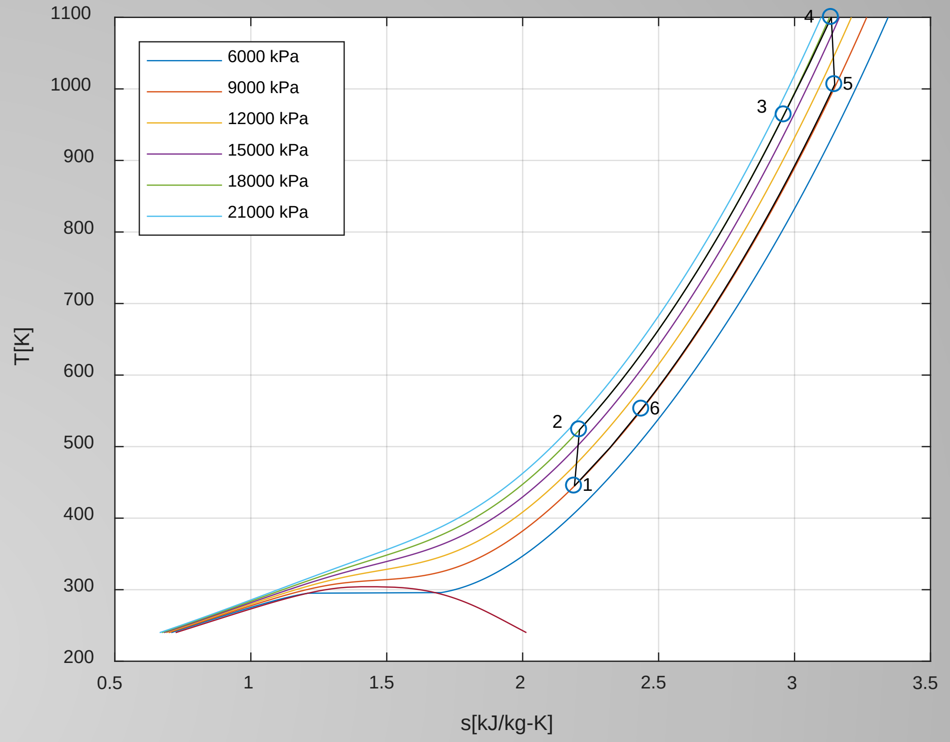


Optimum Radiator Panel Area



Minimum Overall Mass



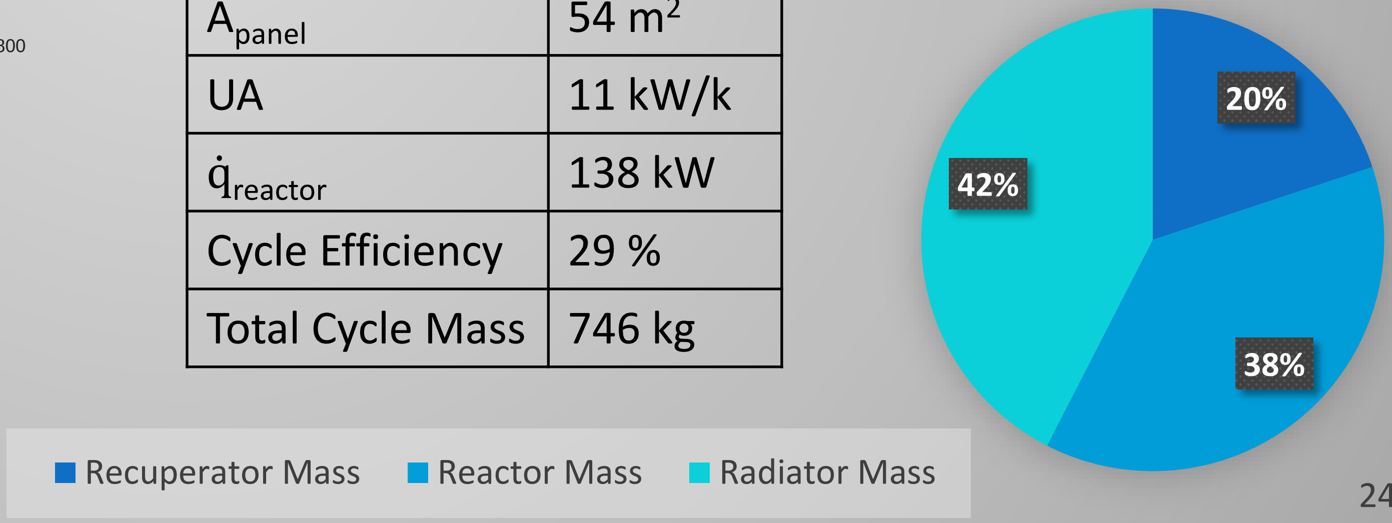


A_{panel}	54 m^2
UA	11 kW/k
$\dot{q}_{reactor}$	138 kW
Cycle Efficiency	29 %
Total Cycle Mass	746 kg

Cycle parameters:

- p1 = 9,000 kPa
- T_4 = 1,100 K
- PR_c = 2
- T_{amb} = 100 K

Fluid: supercritical CO_2



Looking Forward

- Parametric studies of cycle parameters
- Test other working fluids
- Model other cycle configurations
- Integration and optimization with nuclear reactor model

Other Project Contributions

- Testing materials in sCO_2
- Testing turbomachinery barings in sCO_2

Creare

Sandia National Laboratories

SEL

Solar Energy Laboratory

NEUP

Nuclear Energy University Program

U.S. Department of Energy

THE UNIVERSITY of WISCONSIN MADISON

WISCO2

CNERG

Computational Nuclear Engineering Research Group