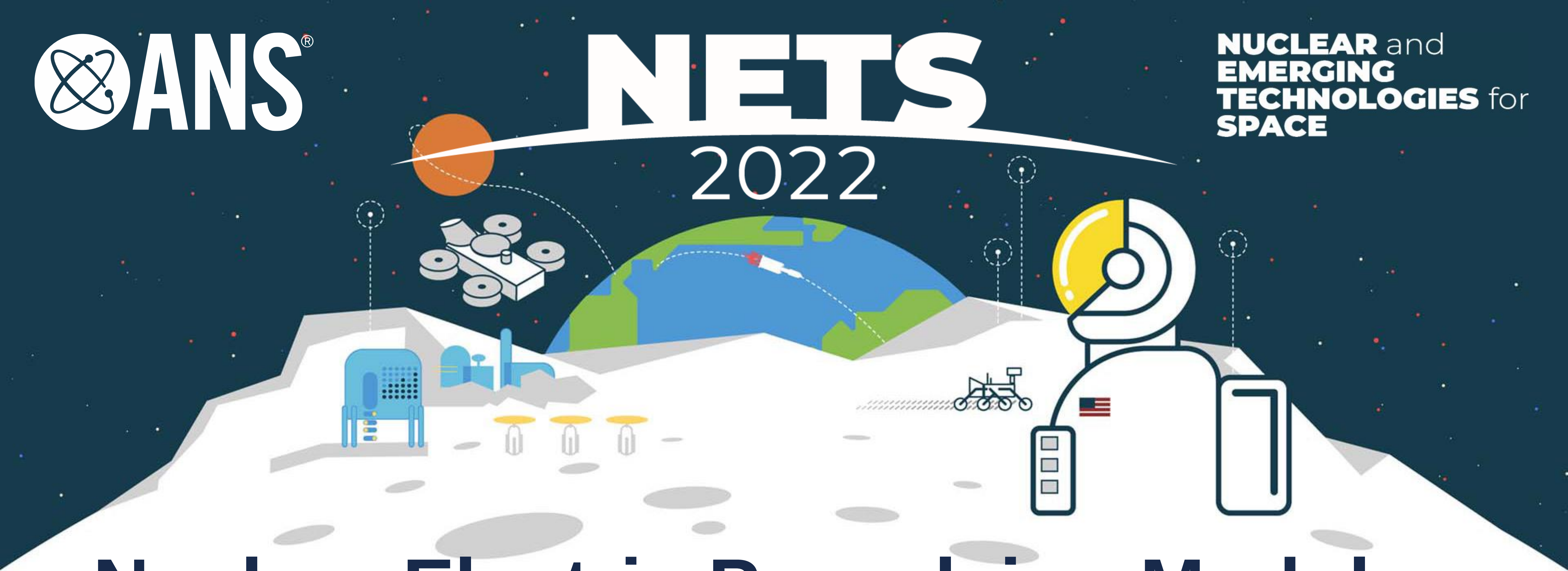


# Nuclear Electric Propulsion Modular Power Conversion Model

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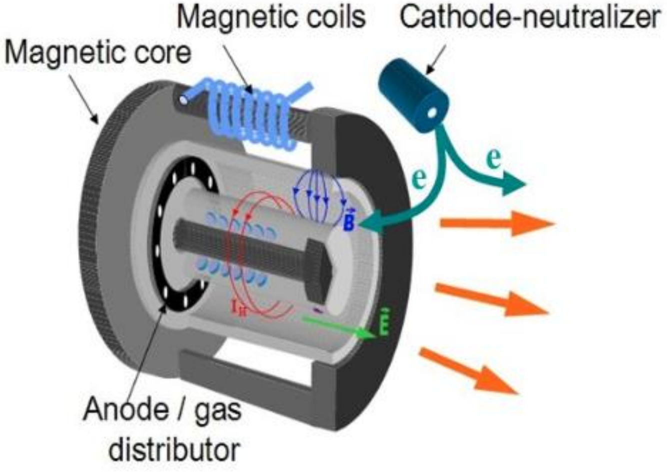
# Agenda

- Introduction
- Working Fluids Considered
- Heat Transfer
- Turbomachinery
- Integrated Model
- Results
- Conclusion/Future Work

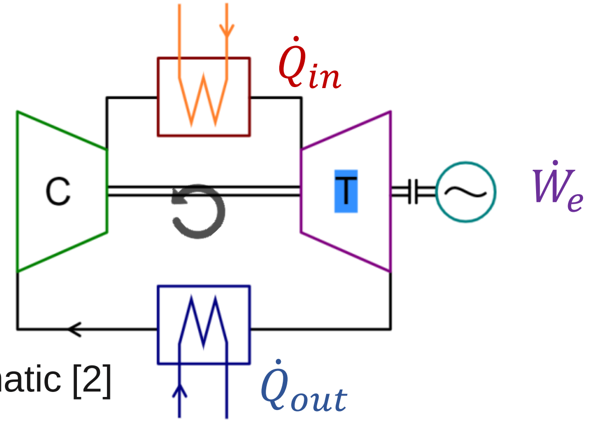
# Introduction

*Nuclear Electric Propulsion (NEP) – nuclear power plant for electricity production*

- NEP uses a nuclear reactor to produce electricity for electric thrusters to accelerate heavy noble gases to provide thrust.
- There are multiple ways of converting thermal energy into electricity for space applications:
  - Brayton
  - Stirling
  - Rankine
- Current research focuses on the Brayton cycle due to scalability, single-phase working fluid, and high TRL.



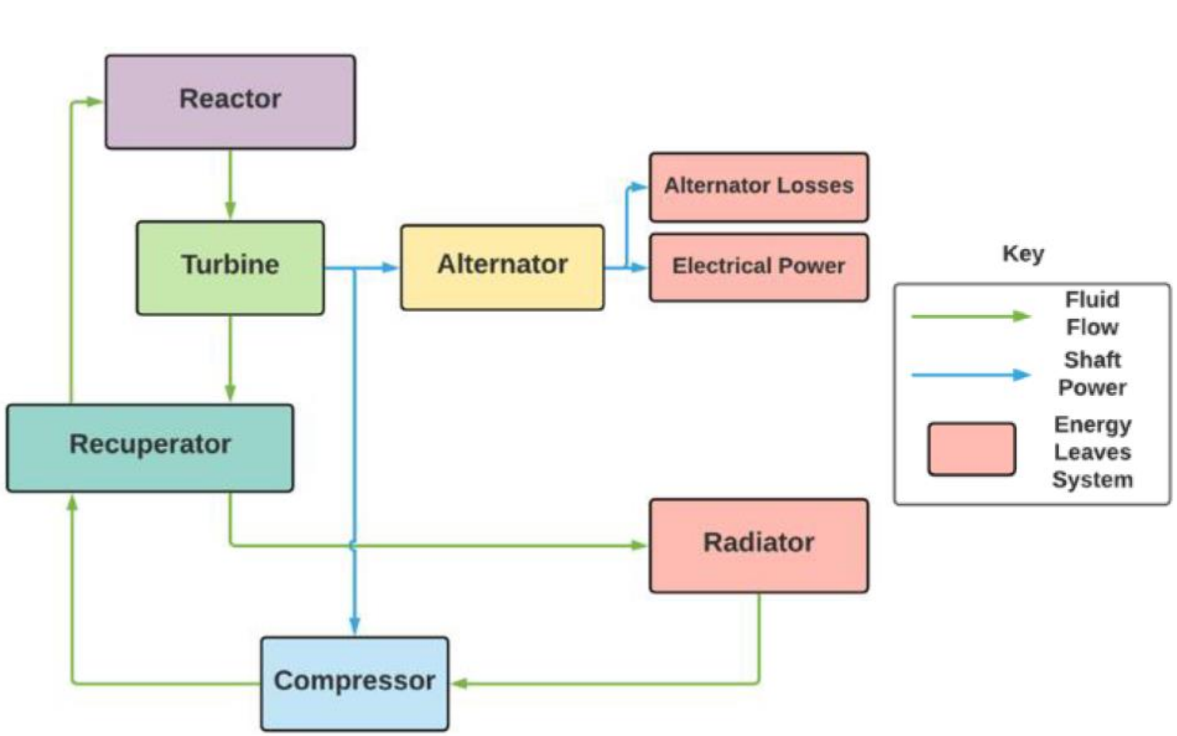

Hall Thruster Diagram [1]

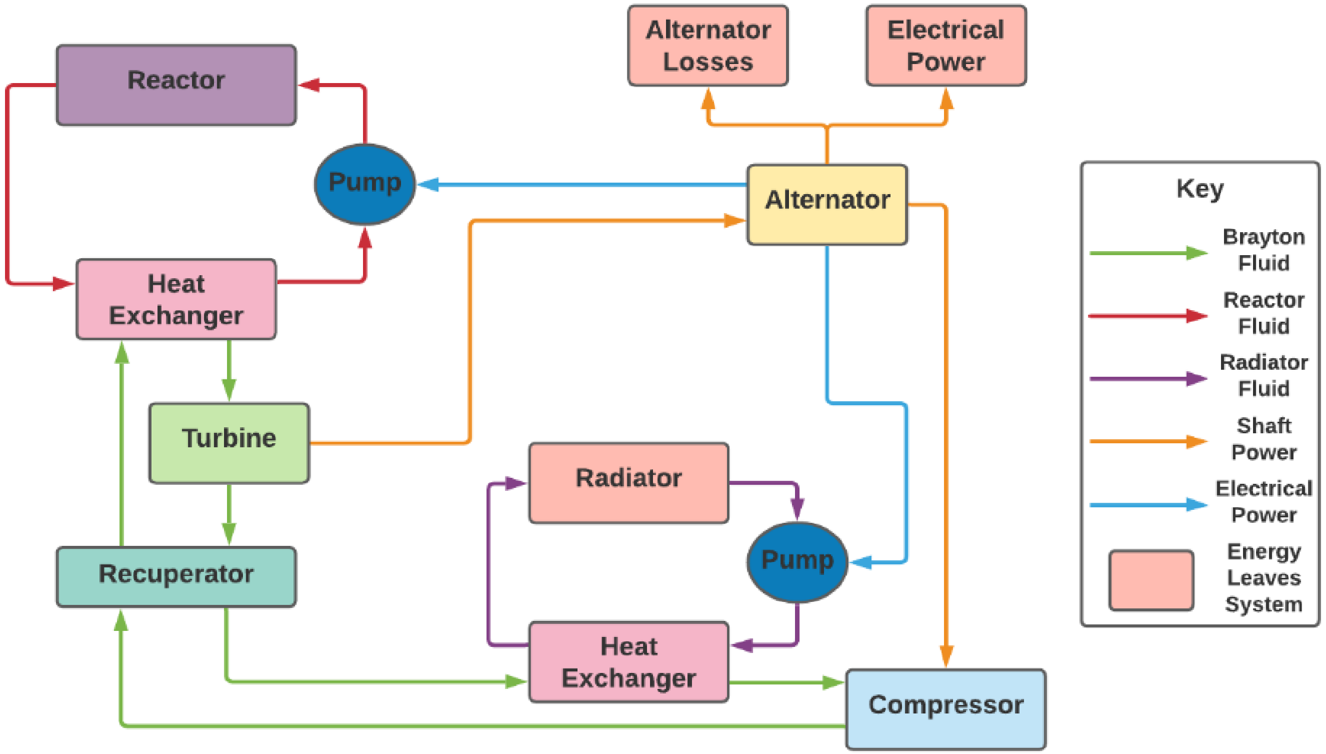



Brayton Cycle Schematic [2]

# Brayton Power Conversion Loop Options

*Heat source is the nuclear reactor, heat sink is the radiator*




***High pressure losses could be incurred at the reactor and radiator, therefore, separate loops with different fluids are considered***

# Working Fluids

*Fluid property libraries allow for variable property considerations*

- Brayton Fluid: Helium (72%) + Xenon (28%) to yield 40 g/mol consistent with the BRU studies [3]
  - Properties for individual fluids are taken from CoolProp [4] and REFPROP [5].
  - To consider mixture ratios:
    - Thermophysical properties use the mass fraction lever rule
    - Transport property mixture correlations developed from kinetic theory [6-8]
  - Future work will consider other mixture ratios of these fluids.
- Reactor Fluid: Lithium
- Radiator Fluid: Eutectic NaK
- Liquid alkali metal properties are taken from Meisl [9].

***Fluid property libraries allow for variable property considerations***

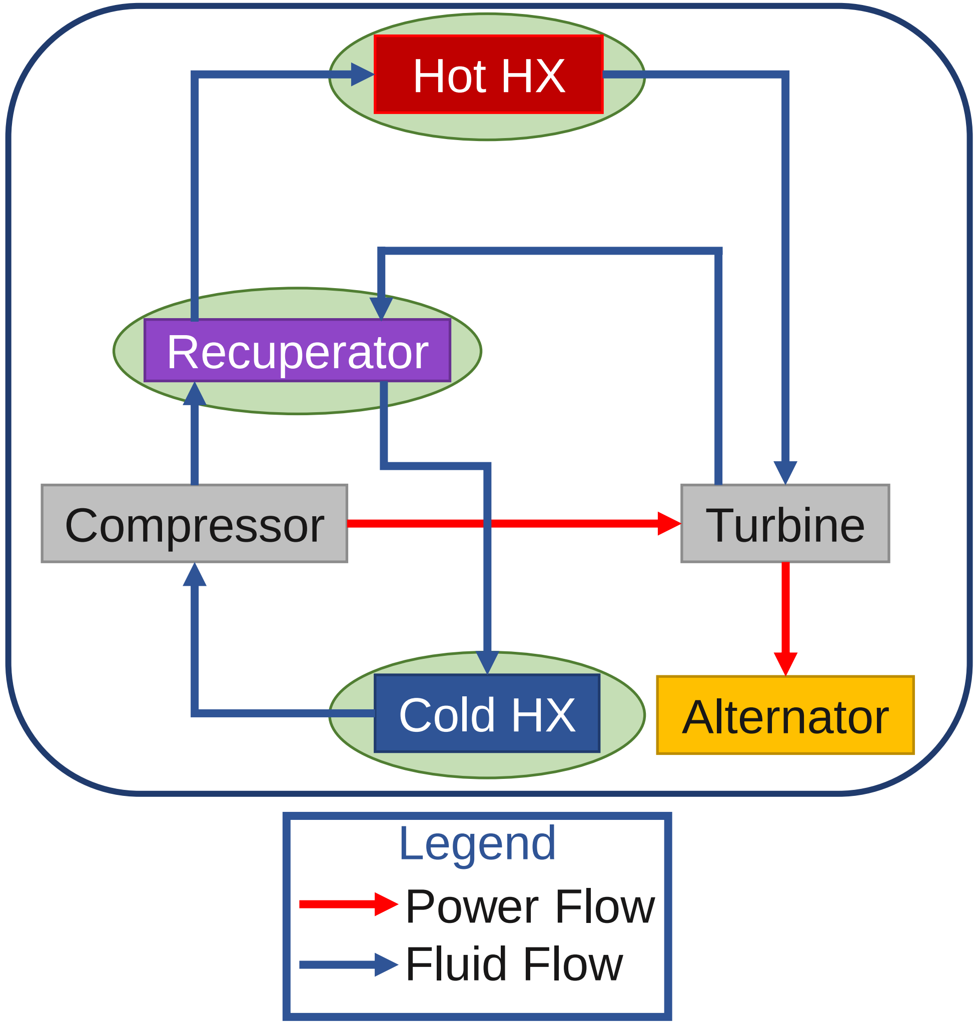
# Heat Transfer Components

*Simple models pave the way for complex component models*

- Reactor
  - Power is based on 1st law enthalpy.
  - Pressure losses are assumed.

$$\dot{Q} = \dot{m}(h_{out} - h_{in})$$
$$T = T(h, P)$$

- Radiator
  - Area is iteratively scaled
  - Frictional pressure losses are calculated. $\Delta P = f\frac{\rho V^2}{2D}$
- Recuperator and Heat Exchangers
  - Based on NTU method.
  - Effectiveness is assumed.
- Future work will consider higher fidelity models of these components.




***Although simple, each component is self-contained and can grow in complexity***

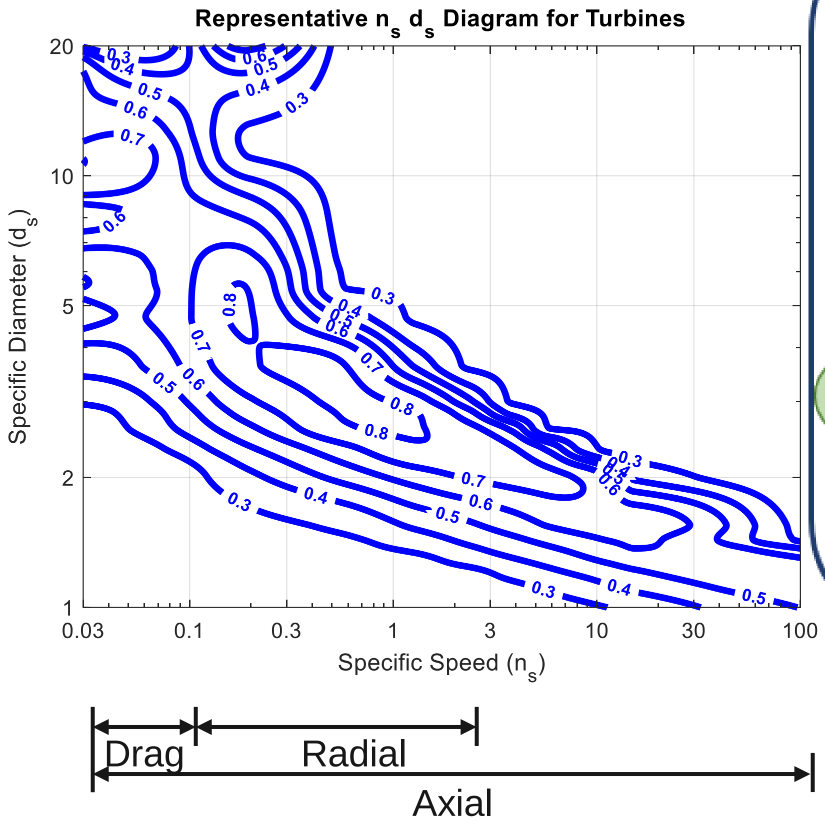
# Turbomachinery

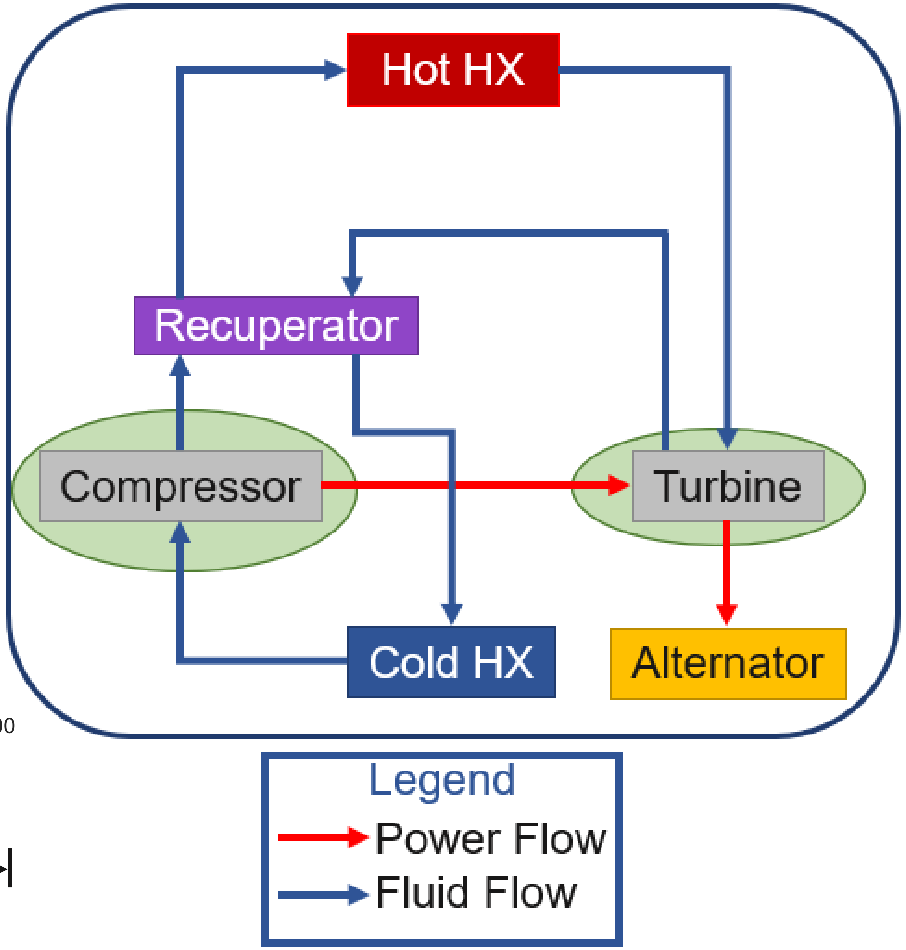
*Complex component models can inform off-nominal operation*

- **Defined by:**
  - Shaft speed $\omega$
  - Efficiency $\eta$
  - Outlet pressure/pressure ratio
- **Solves for:**
  - Diameter $D$
  - Specific speed $n_s$
- Specific speed and specific diameter $d_s$ are related to each other through efficiency $\eta$.

$$n_s = \frac{\omega\sqrt{\dot{\forall}}}{(g_0 H)^{3/4}} = \frac{\omega\sqrt{\dot{m}}}{\sqrt{\rho}(h_{in} - h_{out})^{3/4}}$$

$$d_s = \frac{D(g_0 H)^{1/4}}{\sqrt{\dot{\forall}}} = \frac{D\sqrt{\rho}(h_{in} - h_{out})^{1/4}}{\sqrt{\dot{m}}}$$



# Turbomachinery Validation

- Validation was performed against a NASA Fission Surface Power study [11].
- Efficiency contour plot [10] had to be corrected by 6.5% to better match the results.

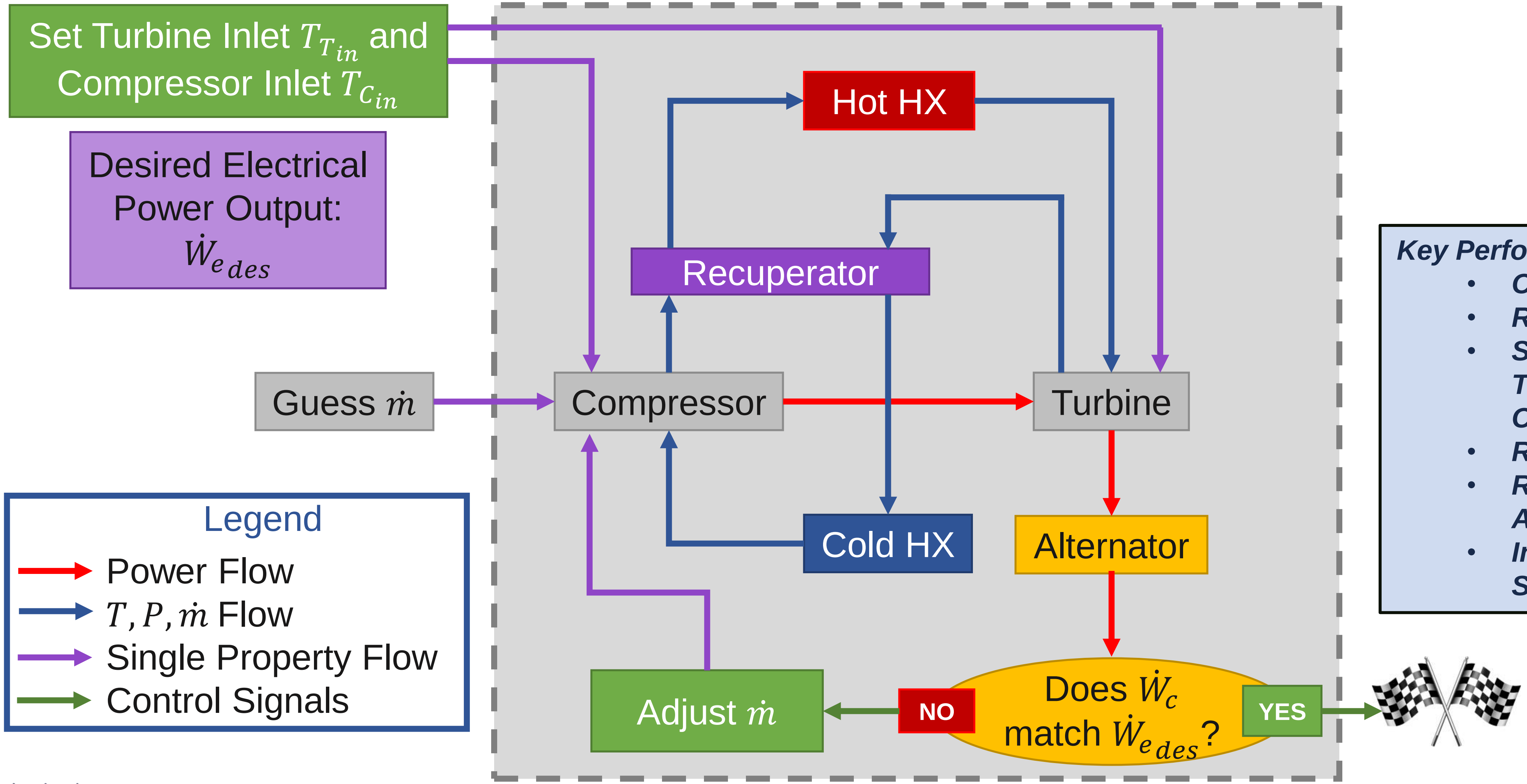
| COMPRESSOR (Pressure Ratio = 2.065; 65,694 RPM) | | | | | |
|---|---|---|---|---|---|
| Inlet Temperature (K) | | Inlet Pressure (kPa) | | Mass Flow Rate (kg/s) | |
| 360.93 | | 330.94 | | 0.54 | |
| Parameter | Reference | Current Model | Difference (%) | Current Model (Corrected) | Difference (%) |
| Efficiency | 84.23 | 79.13 | 6.05 | 84.23 | 0.00 |
| Power | 33339.80 | 36173.60 | 8.50 | 33979.94 | 1.92 |
| Exit Temperature | 428.15 | 433.40 | 1.23 | 429.30 | 0.27 |

| TURBINE (Pressure Ratio = 2.067; 65,694 RPM) | | | | | |
|---|---|---|---|---|---|
| Inlet Temperature (K) | | Inlet Pressure (kPa) | | Mass Flow Rate (kg/s) | |
| 844.26 | | 682.58 | | 0.54 | |
| Parameter | Reference | Current Model | Difference (%) | Current Model (Corrected) | Difference (%) |
| Efficiency | 86.10 | 80.25 | 6.79 | 86.10 | 0.00 |
| Power | 50285.00 | 47090.00 | 6.35 | 50520.00 | 0.47 |
| Exit Temperature | 763.71 | 768.90 | 0.68 | 763.40 | 0.04 |

***As a "Rule-of-Thumb", model-model validation is achieved at less than 4% error while model-experiment validation is achieved at less than 8% error. [12]***

# Solution Method

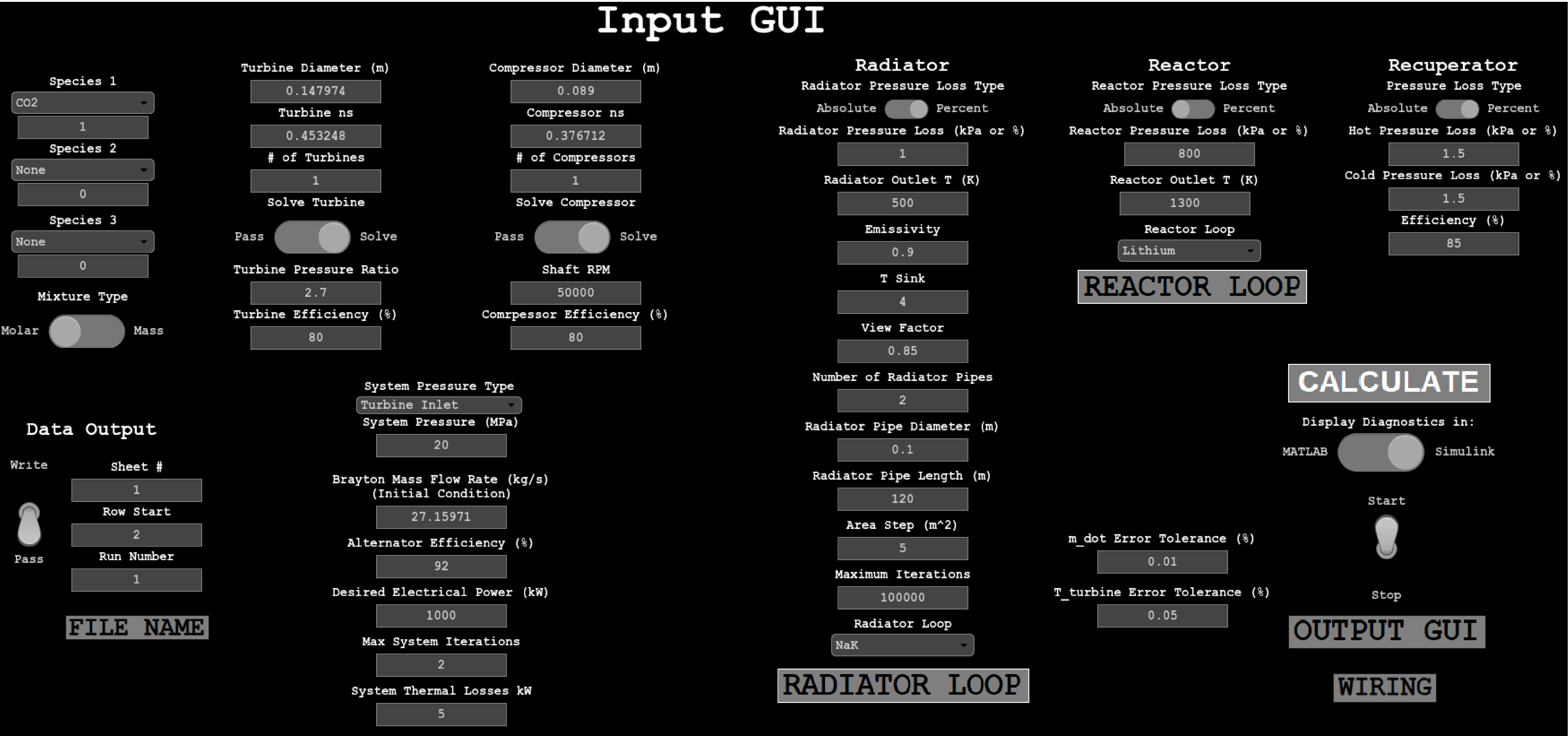
*Iterative solution converging on the cycle mass flow rate*



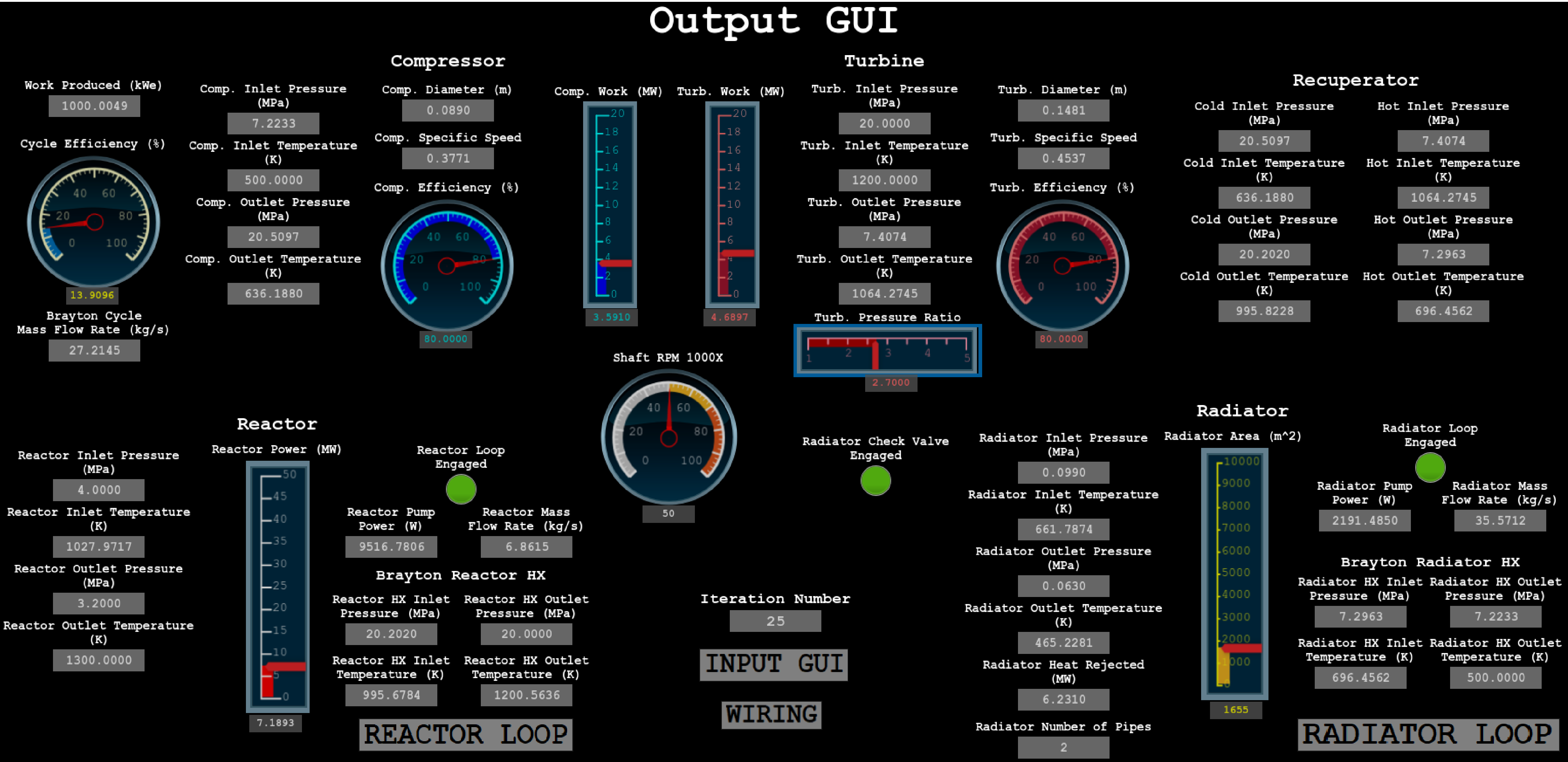

***Key Performance Parameters:***

- ***Cycle Efficiency***
- ***Radiator Area***
- ***Sizing of Turbomachinery Components***
- ***Reactor Power Level***
- ***Radiator Surface Area***
- ***Intercomponent Fluid States***

# Model Input GUI



# Model Output GUI

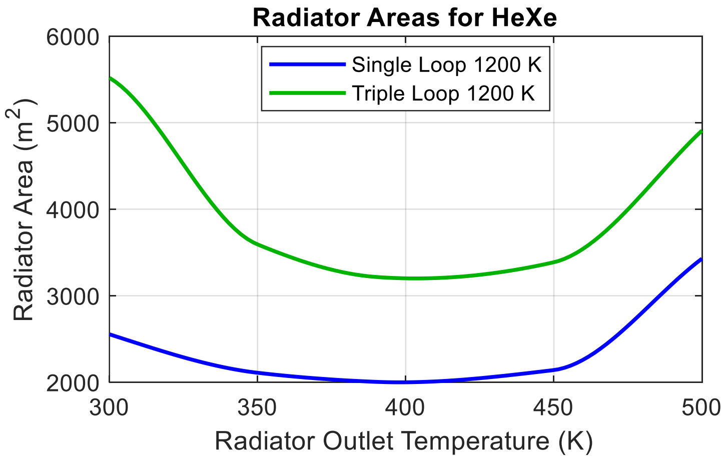


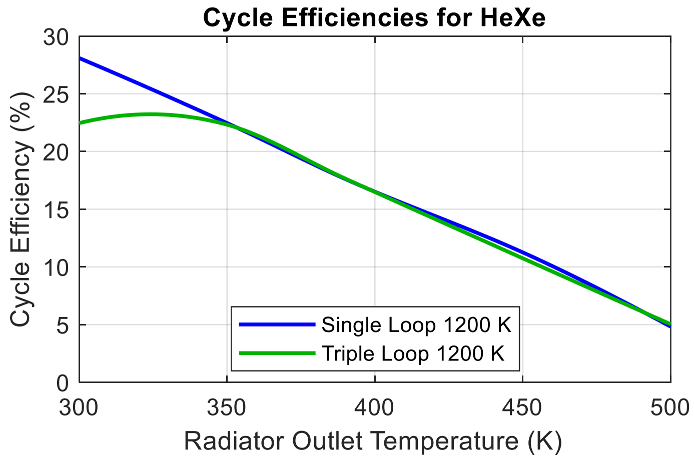
# Results for Varying Radiator Outlet Temperature

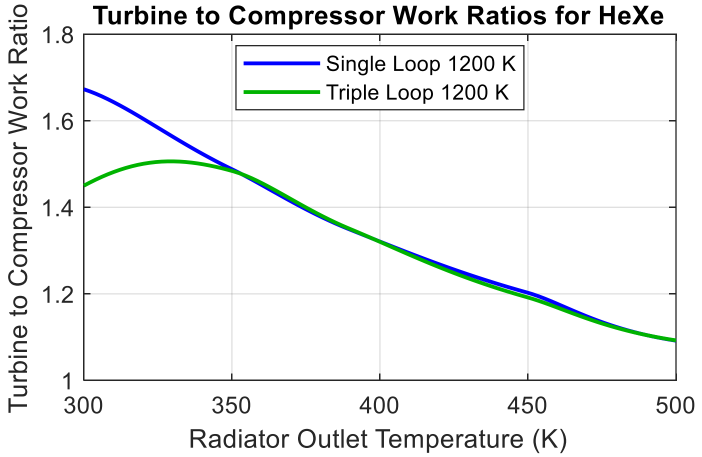
*Low velocities require large components*

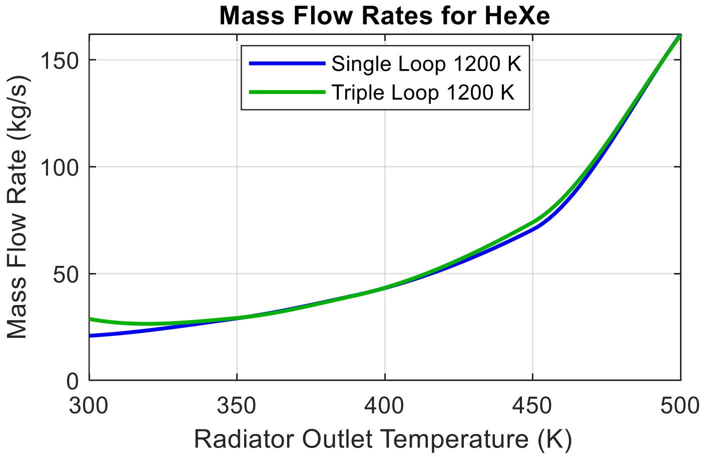
- Electrical power produced was set at 1 MWe.
- Different turbine inlet temperatures and fluid loops were considered.
- The radiator area affects the mass the most and has a minimum value.
- By decreasing the radiator outlet temperature, and thereby decreasing the cycle ΔT, the cycle efficiency decreases.

***At low radiator outlet temperatures, the cycle efficiency is lower for the triple loop due to additional power load from electric pumps.***



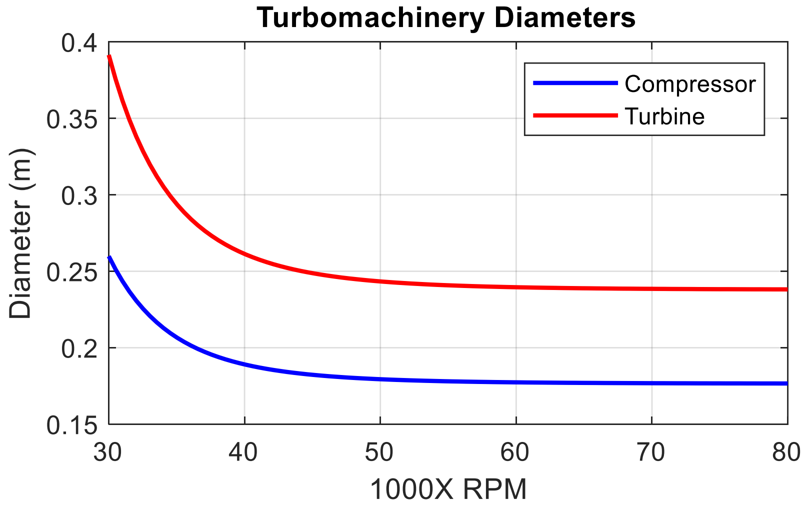



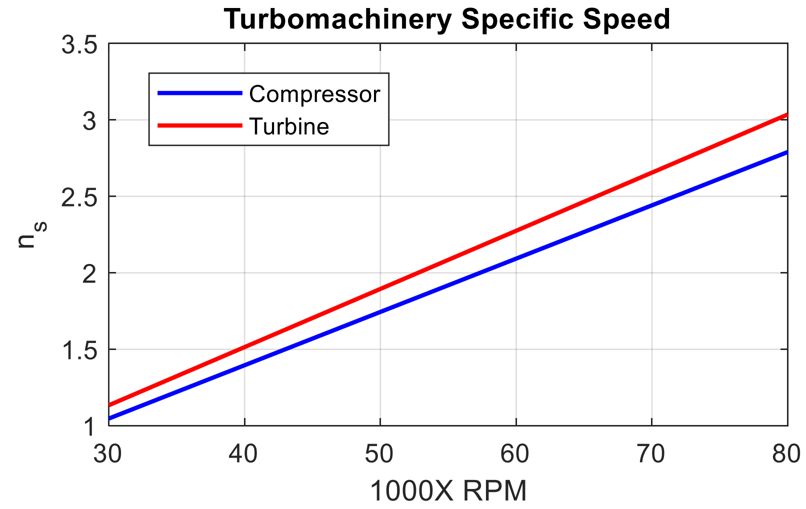
# Results for Varying Shaft Speed

*Low velocities require larger components*

- Turbomachinery diameters are secondary mass drivers
- Considered: 1 MWe and 80% turbomachinery component efficiency.
- Higher velocities show to decrease the turbomachinery diameters but increase the strain on the roots of the blades.
- Specific speed increases linearly.

***Depending on the material chosen for these components, a mass estimation can be made using these values.***



# Conclusions / Future Work

*NEP modular power conversion model*

- Higher fidelity turbomachinery informs system masses and can predict off-nominal performance.
- Different options in the GUI allow for different use cases to be examined and design methodologies implemented.
- Future work will consider:
  - High fidelity heat exchanger and reactor neutronics spline fit results.
  - Trades involving different types of heat exchangers.
  - Reactor heat pipe blocks and accompanying heat exchanger.
  - Different HeXe mixture concentrations.

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