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TEMPERATURE AND POWER SPECIFIC MASS SCALING FOR LEU CLOSED-CYCLE BRAYTON SYSTEMS FOR SPACE SURFACE POWER AND NUCLEAR ELECTRIC PROPULSION

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The specific mass (or mass per unit power) is a fundamental performance metric in space power systems. For surface power, a low specific mass reduces launch costs and lander size. For nuclear electric propulsion, a low specific mass enables fast transit with within the solar system [1]. Studies on specific mass have typically focused on point designs and have not adequately explored the design space and scaling of specific mass. Previous research by the author has studied closed cycle Brayton power conversion and has shown that specific mass is a strong function of temperature and power [2]. This paper continues this research and explores the design space for radiatively-cooled closed nuclear Brayton systems with an emphasis on temperature and power. The resulting analyses show the scaling laws for specific mass.

I. System Model

The Brayton system thermodynamic and mass model is derived from previous research and is composed of the components listed in Figure 1 and Table 1 [1].

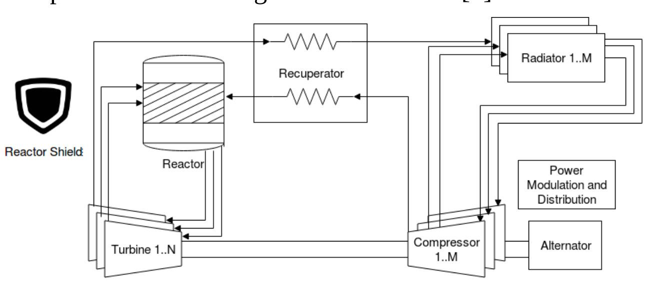

Fig. 1 Brayton Power System Model.

Component	$\alpha_{component}$	Mass Model	Minimize $\alpha_{component}$
Reactor	High	Design	↑ Power
Shield	High	Estimate	↑ Power
Radiator	High	Design	↑ Temp
Power Modulation	Low	Estimate	Other
Compressor	Low	Trend	↑ Power
Turbine	Low	Trend	↑ Power
Alternator	Low	Trend	↑ Power
Recuperator	Low	Design	↑ ΔT

Table 1: Brayton Cycle Components and Power and Temperature Trends.

Each of the components in the system have a component specific mass $\alpha_{componet}$. The sum of each $\alpha_{componet}$ yields the system specific mass α_{sys}.

$$\alpha_{sys} = \frac{m_{sys}}{P_{sys}} = \sum \frac{m_{component}}{P_{sys}} = \sum \alpha_{component} \quad (1)$$

Each component in the system is primarily a function of temperature or power with the exception of the power modulation and conversion system (PMAD).

$$\alpha_{componet}(P) \quad \text{or} \quad \alpha_{component}(T_{hot})$$

For example, a radiator's mass will scale linearly with power, but will scale with temperature to the fourth power. A reactor shield scales logarithmically with power and has little relationship to temperature. Because of the intrinsic coupling of power and temperature with regards to specific power, any design must be evaluated with regards to both parameters.

$$\alpha_{system}(P, T_{hot})$$

Besides T_{hot} and P, there are other variables in the design space shown in Table 2.

Variable	Variable Name	Minimize α
T_{cold}	Cycle Cold Temperature	Optimize
η_{recoup}	Recuperator Efficiency	Optimize
η_{comp}	Compressor Polytropic Efficiency	Maximize 85%
η_{turb}	Turbine Polytropic Efficiency	Maximize 85%
η_{alt}	Alternator Efficiency	Maximize 95%
PR	Compressor Pressure Ration	Optimize
p_{max}	Compressor Outlet Pressure	Optimize
$\Delta p_{reactor}$	Reactor Pressure Drop	Set Point ≈ 1%
$\Delta p_{radiator}$	Radiator Pressure Drop	Set Point ≈ 1%
Δp_{recoup}	Recuperator Pressure Drop	Set Point ≈ 1%

Table 1: System Parameters in Brayton Cycle Model.

Some of these variables have a strong dependence on pressure and temperature and need to me optimized. For example, is the cycle cold side temperature T_c must be optimized. Too hot and it will achieve a poor thermodynamic efficiency, too low and the radiator heat rejection system will increase prohibitively in mass. Other variables should be maximized to as high of value as possible, while still being grounded in reality. For example, a polytropic turbine efficiency of 85 percent is considered state-of-the-art and has been demonstrated in many turbine designs. A pressure drop is inherent in any heat exchange device. Pressure drops of around one percent are typically optimal for a system. Higher pressure drops cause compressor work to greatly increase, and lower pressure drops suggest that the heat exchanger could be redesigned to be more compact and reduce significant mass.

For this analysis, thousands of data points were collected that represent a sampling of the output of the system model over a ranges in temperature from 900 K to 3200 K and total power from 10 kW_e to 1 GW_e.

II. Determining Optimized Values

There are four parameters T_{cold} , η_{recoup} , PR, and p_{max} which needed to be optimized. To optimize the specific mass of the system a better understanding is necessary. For the pressure ratio, PR, it was found that a value of approximately 1.5 - 1.9 was optimal. Too high of pressure ratio required more complex and multi-stage turbomachinery. Too low of pressure ratio and pressure drops in the system became relatively more costly for the compressor. The maximum pressure p_{max} could also be optimized for a design. Higher pressures help by lowering pressure drops in components, however the walls of the pipes on various components exposed to space also needed to be thickened to withstand the high pressures. As the total power increases higher pressures help keep features such are reactor coolant channels small. Generally, values between 500 kPa and 10 MPa where found to be optimal. These two pressure-based parameters were able to be solved for by perturbing their values and iterating toward a minimum specific mass and generally well-behaved functions with small effects on α within the relevant domain.

The parameter T_{cold} and η_{recoup} have a significantly larger impact upon α in the relevant domain and these parameters deserve greater exploration. Figure 2 shows the relationship of specific mass as a function of cold and hot temperature.

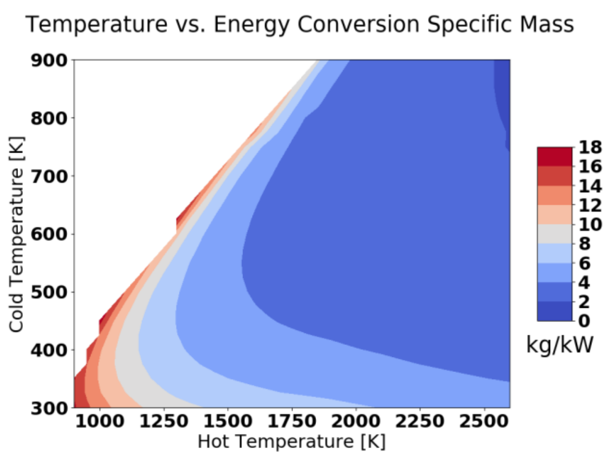

Fig. 2 Cold Temperature Design Space [1].

For a given hot temperature there is a very clear linear trend line for an optimal cold temperature. Hotter cold temperatures reduce the mass of the radiators; however, they quickly cause a large increase in the specific mass is they are too hot to produce a reasonable thermodynamic cycle. There is a clear linear trendline that optimizes specific mass over the region of interest.

The η_{recoup} is more nuanced. A recuperator's size and mass is related to the efficiency of the heat exchange as well as the total difference in temperature between the hot and cold sides.

$$\alpha_{recuperator}(\eta_{recoup}, T_{hot} - T_{cold}) \quad (2)$$

It was found that for a given hot temperature and optimized cold temperature is an optimum recuperator efficiency such as show in Figure 3.

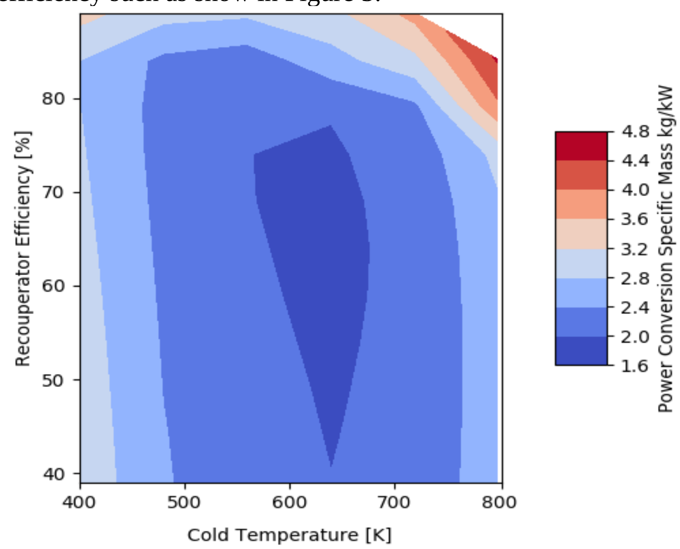

Fig. 3 η_{recoup} vs. T_{cold} for a T_{hot} of 1600 K.

As the T_{hot} goes up it appears that the optimal recuperator efficiency drops. This is likely because higher temperature radiators have a relatively lower specific mass, and the recuperator begins to become more of a mass factor in the system. Past research has questioned whether recuperates are desirable [3]. This research indicates that at lower temperatures recuperators are important, but less important for higher temperatures.

III. System Model Analyses

Based on the data generated in Section II, the optimal specific mass can now be determined directly as a function of hot temperature and total power.

III.I. Power Scaling Components

The reactor, shield, and turbomachinery components scale strictly as a function of power. Three difference Pylons reactors (50 kW_e, 100 kW_e and 1 MW_e) and with a one pi radiation shield were used to determine a specific mass scaling of the reactor and shield [4]. The trend line is shown in orange in Figure 4.

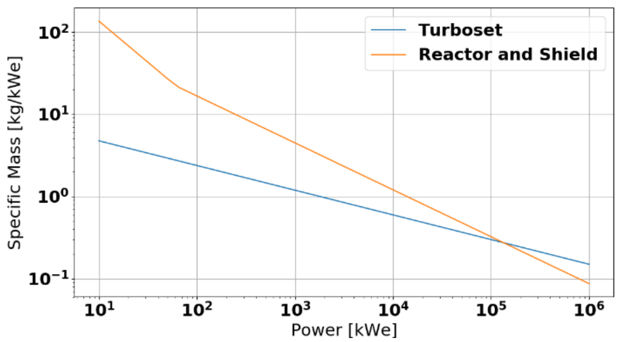

Fig. 4 Power Scaling of Turboset, Reactor, and Shield.

There are two regions in the orange line. Below 50 kW_e the reactor is criticality limited. Above 50 kW_e the reactor is burn-up limited to achieve a 10-year lifetime. The turbomachinery scaling in Figure 4 is shown in blue and was a simple correlation from [3].

IV.II. Temperature Scaling Components

The radiator component scales with temperature to the fourth power and the recuperator scales as shown in Equation 2. The specifics of the radiator design are detail in [1]. The scaling of the specific mass of the recuperator and the radiator is show in Figure 5.

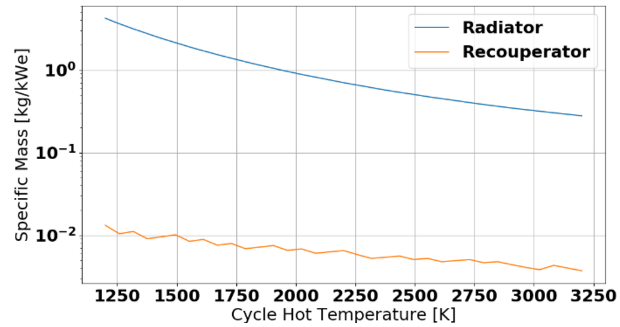

Fig. 5 Temperature Scaling of Radiator and Recuperator.

III.III. Combined Power and Temperature Scaling

Figure 6 shows the power and temperature scaling combined into a contour plot. All specific mass components are included except for the PMAD. At low power and low temperature, the specific mass is suboptimal. For a fixed power a lower specific mass can be attained by increasing temperatures, however it is a diminishing gain as higher power asymptotes to a minimum specific mass. For a fixed-power system it is vice versa. For a given temperature there is an optimum power domain to minimize specific mass that exists in the "knee of the curve" in the contour plot. Low temperature technologies will be competitive at low powers. The operational temperatures for stainless steel and Inconel 718 are shown in Figure 6 to gain a better understanding of materials requirements. Higher temperatures would likely require ceramic technology, especially for the turbine and reactor.

Figure 7 shows the power and temperature scaling for higher temperatures with an approximate trendline going through the optimal kneel of the curve.

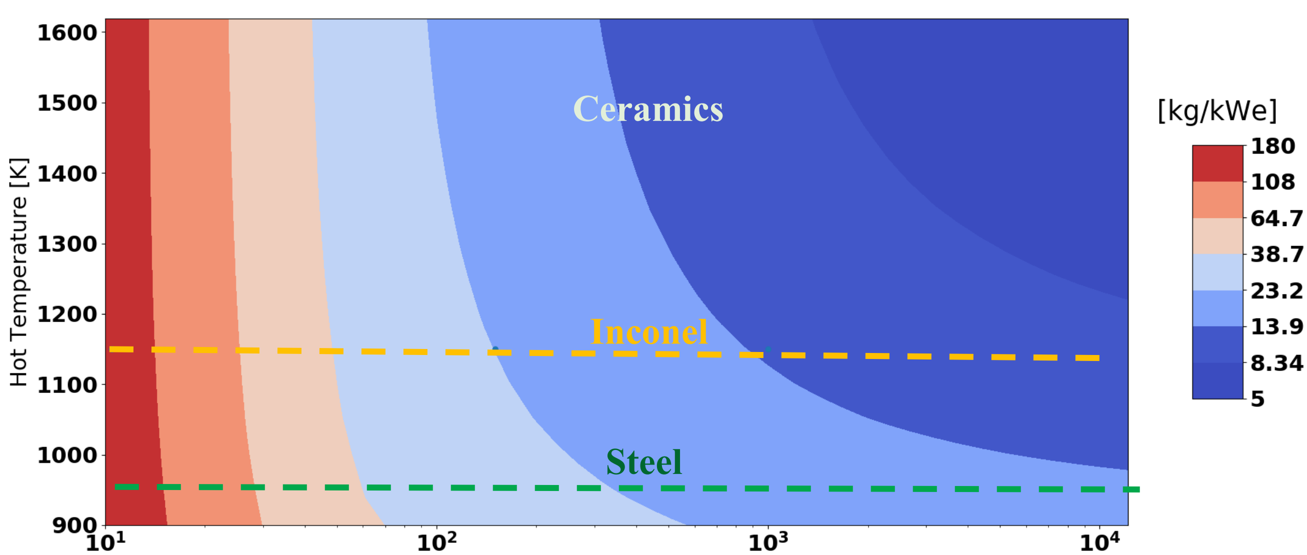

Fig. 6 Scaling Specific Mass with Power and Temperature For All Components Except PMAD.

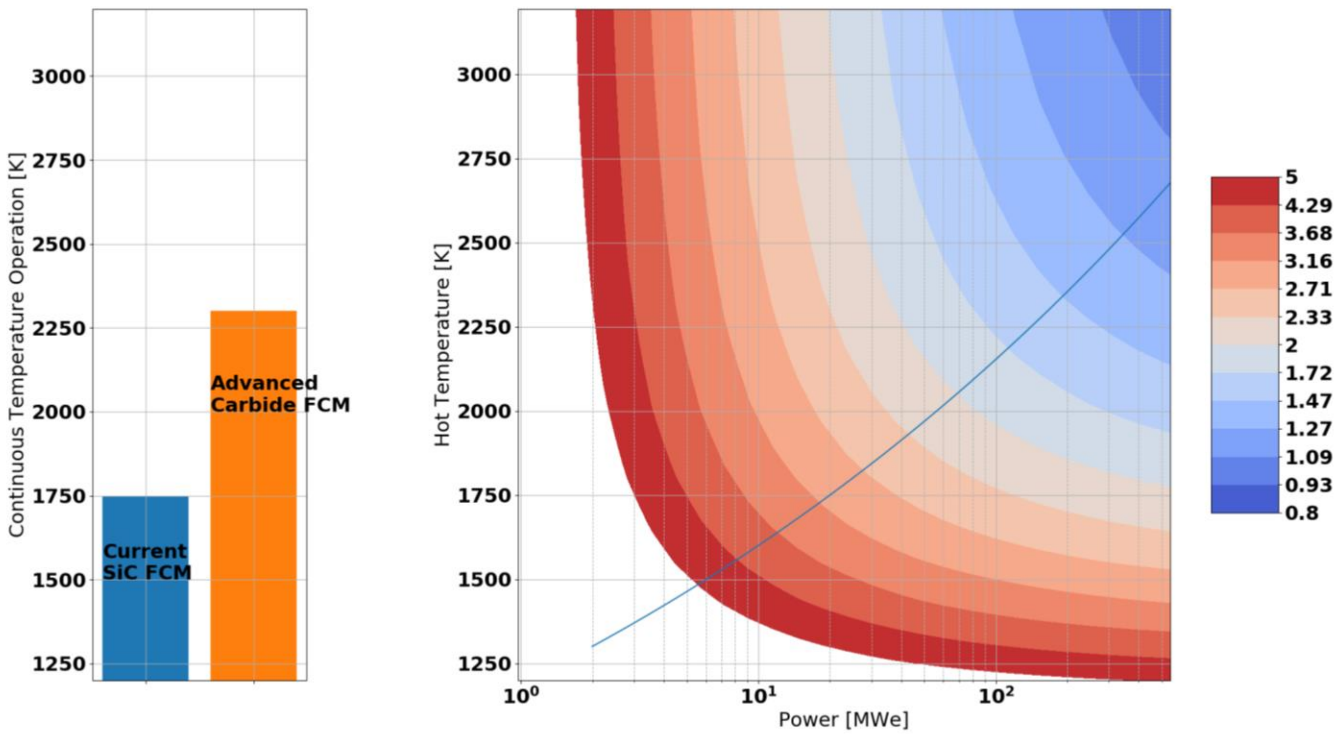

Fig. 7 Scaling Specific Mass with Power and Temperature for High Temperatures All Components Except PMAD.

IV. CONCLUSIONS

The relationship between specific mass, power, and temperature is important to understand. Different missions such as surface power and fast nuclear electric have different specific mass requirements. Using the analysis from this research the desired power and total mass of a vehicle can be quickly ascertained. For example, fast human nuclear electric propulsion requires a specific power of 10 kg/kW_e or less [1]. Using a margin with a factor of two and allocating a PMAD specific power of 1.5 kg/kW_e a power level of 5 MW_e and a hot temperature of 1500 K would enable such a mission. That vehicle would have a mass of less than 50 metric tons. Figure 8 has mass on the x-axis and other parameters of interest on the y-axes. Table 3 uses Figure 7 to assign an optimal design to fit in the payload of several launch vehicles.

High temperature materials are key for low specific mass. The extreme temperatures shown in Figure 7 can be achieved by using the advanced carbides developed by USNC-Space [5] and are shown in the bar chart. For advanced nuclear systems ceramics will be an important technology for both the reactor and power conversion systems. Currently terrestrial turbomachinery is working on ceramic blades that can tolerate temperature well over 1800 K but typically require significant maintenance, use film cooling, and have much greater pressure ratios.

V.I. Limitations and Future Work

In future research a more in-depth analysis would be conducted and consider different reactor architectures and other limitations in greater detail. For example, some types of reactors would not be as burn up limited and at higher powers there are more thermal limitations that were not included in this analysis. In addition, more analysis would be necessary to look at high power designs.

PMAD is still a strong unknown in this analysis. Advances in GaN and SiC semiconductor technologies should enable α_{PMAD} vales of close to 1 kg/kW_e [6]. PMAD is also somewhat unique to the final power application and has been subject to many recent advanced in semiconductor technologies.

While the absolute values of the specific mass are dependent upon the models and assumptions of the component models, the trends in this paper should apply to all Brayton cycles in a radiative heat rejection environment. Many of the specific nuances in this analysis exist because of the radiator scaling. For a convective or conducive heat rejection environment. The design space would significantly differ.

V.II. Miscellaneous

Supercritical Brayton cycles have some strengths. However, supercritical technologies such as supercritical CO_2 needs to be compressed near their critical temperature to achieve a high efficiency. This pins the cycle's cold temperature. For supercritical CO_2 the critical temperature

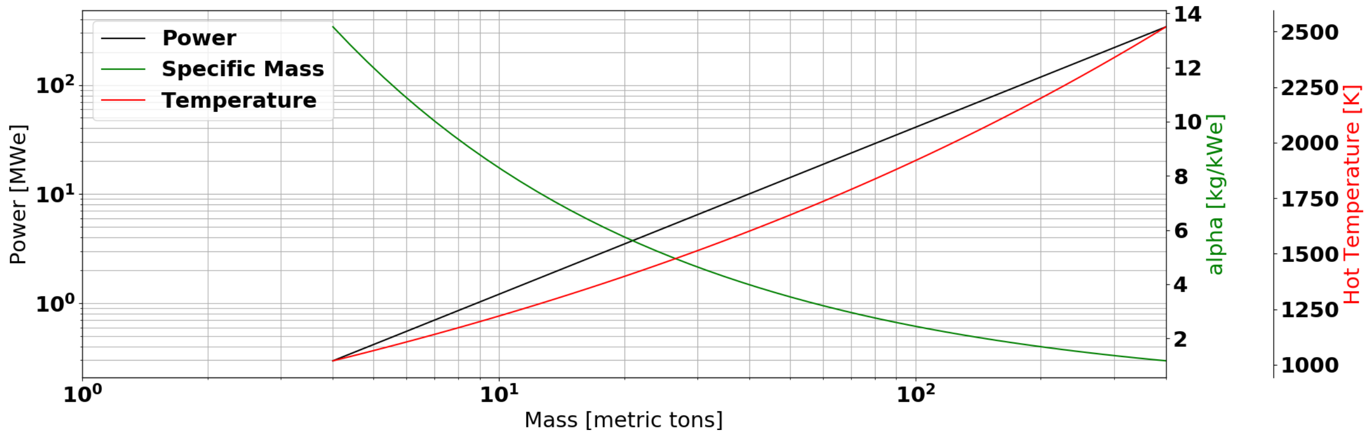

Fig. 8 Mass, Specific Mass. Power and Temperature of Optimized Designs in the Knee Curve of Figure 7, No PMAD.

Launch Vehicle and Location	Payloads [metric tons]	Optimal Power	Optimal Temperature [K]	Specific Mass [kg/kW$_e$]
Falcon Heavy LEO	63	10 MW_e (20 MW_e)	1750	6 (3)
Falcon Heavy GTO	26.7	2 MW_e (4 MW_e)	1550	10 (5)
Falcon Heavy Mars	16.8	1.5 MW_e (3 MW_e)	1450	14 (7)
New Glen LEO	45	7.5 MW_e (15 MWe)	1700	8 (4)
Blue Moon	5	200 kW_e (400 kW_e)	1150	24 (12)
Falcon Super Heavy LEO/SLS Block II	100	25 MW_e (50 MW)	1900	5 (2.5)
Vulcan LEO	35	3 MW_e (6 MW_e)	1625	10 (5)

Table 3: Different Launch Vehicles Pairing Following the Knee of The Curve in Figure 7 and 8. A safety factor of 2.0 was used to reduce performance to be conservative. Values in Parentheses do not have a Safety Factor.

is close to room temperature and would have a higher specific mass with the radiators despite having a higher efficiency. There may be instances where supercritical cycles could pose an advantage; however it would only be at a specific power and temperature.

Rankine cycles (typically liquid metal) can be very competitive with Brayton cycles. However, the boiling point of various working fluids fixes the cold temperature of the Rankine cycle (similar in nature to how supercritical Brayton cycles fix the cold temperature). Rankine cycles will outcompete Brayton cycles, but only in certain temperature and power ranges that are suitable to the boiling point of the fluid at a reasonable pressure.

A standard Brayton cycle has the advantage of being very scalable in temperature and power within the limits of its materials. In addition, a Brayton Cycle has no issues operating in a low-gravity environment and little to no operational issues dealing with phase changes in the working fluid during off-nominal operation.

A high efficiency is usually associated with a good system. However, in the case of this research, a high efficiency is not necessarily a boon. Higher efficiency thermodynamic cycles have a lower colder temperature causing an increase in the specific mass of the radiators.

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