Influence of parameters on different Brayton cycle configurations: a thermodynamic and sensitivity analysis.

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Abstract - This study compares five Brayton cycle configurations—simple, intercooled, reheat, regenerative, and complete—using thermodynamic modeling with real-gas air properties at a fixed thermal input of $Q_{\text{core}} = 120$ MW. Component-level models account for isentropic efficiencies and pressure losses in heat exchangers. A Sobol global sensitivity analysis identifies the dominant parameters affecting net power output W_{net} and thermal efficiency η. Results show that turbine inlet temperature and component isentropic efficiencies have the strongest influence on cycle performance, providing quantitative guidance for gas turbine design optimization.

Keywords: Brayton cycle, thermodynamic analysis, Sobol sensitivity analysis, efficiency optimization, parameter study

Thermodynamic cycles serve as the backbone of modern power generation systems, with the Brayton cycle being a pivotal technology for gas turbine engines used in power plants and aircrafts [1]. Since its inception, the Brayton cycle has undergone significant evolution, driven by advancements in high-temperature materials, aerodynamic design, and combustion technologies [2]. Historically, early implementations focused on proving feasibility, but the mid-20th century saw rapid refinement for aerospace applications [3].

Today, the cycle is not only central to traditional propulsion but is also increasingly adapted for hybrid systems integrating renewable energy sources. In the context of global energy challenges, such as the vital need for sustainable power generation, the Brayton cycle offers a pathway to reduce emissions while maintaining high performance [4]. Advanced cycle configurations—such as those incorporating intercooling, reheat, and regeneration—have been developed to exploit thermodynamic potentials further [5].

Although existing studies have examined these configurations [6], the influence of individual design parameters on cycle performance remains insufficiently quantified. Local sensitivity approaches are limited in their ability to account for parameter interactions. To address this gap, we apply Sobol's variance-based global sensitivity analysis [7, 8] to five Brayton cycle variants, with the objective of identifying key design levers for advanced thermal systems.

1. Thermodynamic Modeling and Sensitivity Analysis

1.1. Thermodynamic Modeling

In this study, the Brayton cycles are modeled by considering eight key performance parameters of their constituent components, summarized in Table 2.holding temperature T_{in} is fixed by the available cooling medium (ambient air or cooling water); it is treated as a variable in the

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sensitivity analysis to account for site-dependent ambient conditions. The compressor is characterized by its outlet pressure (or equivalently, the pressure ratio) and isentropic efficiency, which are crucial for determining the compression work [9]. The turbine performance is similarly defined by its isentropic efficiency, governing the work extraction from the high-temperature gas stream. The heat exchangers are modeled by incorporating a pressure drop factor to realistically capture pressure losses across these devices [10]. A recuperator is included based on its effectiveness, which quantifies the fraction of energy recovered from the exhaust gases to preheat the incoming air. For cycles with intercooling, the intercooler outlet temperature defines the cooling achieved between compression stages.Finally, the temperature of the primary heat exchanger outlet determines the maximum cycle temperature, which has a direct impact on thermal efficiency and net power output. The mass flow rate is determined to maintain the prescribed thermal input $Q_{\text{primary}} = 120$ MW.This thermal power level is representative of medium-scale industrial gas turbines (100–150 MW class) used in combined heat-and-power applications, enabling comparison with published benchmark data. T_{H} is the temperature of the hot source and T_{C} that of the cold sink. This comprehensive component-level approach enables an accurate and detailed representation of the thermodynamic processes, facilitating a robust sensitivity analysis of the Brayton cycle performance with respect to variations in these key parameters. The governing equations for each component are summarized in Table 1.

Table 1 : *Governing equations of each device*

Process	**Equation**
Pressure drop	$P_{\text{out}} = P - \Delta P$
Energy conservation	$\dot{m}(h_{\text{out}} - h_{\text{in}}) = \dot{Q} + \dot{W}$
Compressor	$h_{\text{out}} = h_{\text{in}} + (h_{\text{out}}^{\text{is}} - h_{\text{in}})/\eta_{\text{comp}}$
Turbine	$h_{\text{out}} = h_{\text{in}} - \eta_{\text{turb}}(h_{\text{in}} - h_{\text{out}}^{\text{is}})$
Properties (CoolProp)	$h = f(P, T), \quad s = f(P, T)$
Recuperator	$\varepsilon_{\text{recup}} = (T_{\text{out,c}} - T_{\text{in,c}})/(T_{\text{out,h}} - T_{\text{in,c}})$

The pressure drop ΔP_{HX} is set as an arbitrary constant (Table 2), as no detailed heat exchanger model is implemented in this study. In the following analysis, we investigate five specific Brayton cycle configurations to assess the impact of architectural changes: the **conventional** baseline cycle; the **reheat** cycle [5]; the **regenerative** cycle [11]; the **intercooled** cycle [12]; and the **complete** cycle [6], which integrates all three enhancements to simultaneously maximize power and efficiency. These configurations allow us to systematically assess the impact of each process modification and could be visualized in Figure 1. All the key parameter values are listed in table 2. The component-level equations were derived from Çengel and Boles [1], which serves as the validation baseline; the reference performance values in Table 3 are consistent with the cycle analyses presented therein.

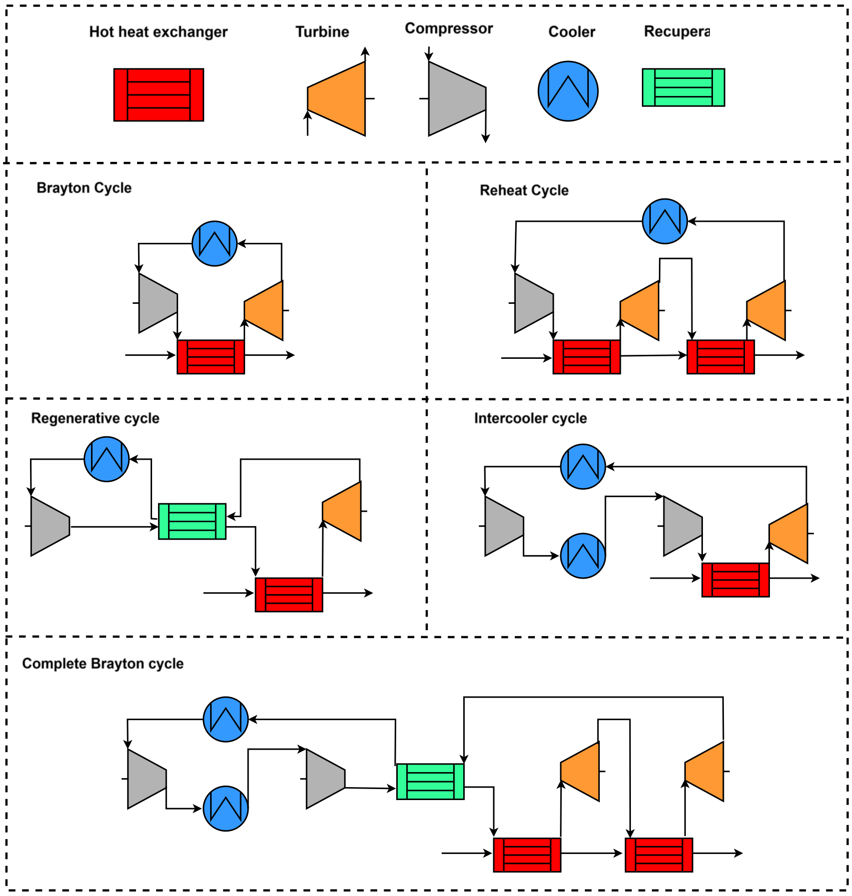

Figure 1 : *Illustration of the 5 Brayton cycle configurations studied.*

Table 2 : *Reference values and sensitivity analysis boundaries for the Brayton cycle parameters*

Parameter	**Symbol**	**Ref.**	**Min**	**Max**	**Units**
Compressor Inlet Temperature	T_{in}	15	0	30	°C
Compressor Inlet Pressure	P_{in}	1	–	–	bar
Compressor Pressure Ratio	π_{comp}	7	5	10	–
Compressor Isentropic Efficiency	η_{comp}	0.85	0.75	0.90	–
Turbine Isentropic Efficiency	η_{turb}	0.85	0.75	0.90	–
Recuperator Effectiveness	$\varepsilon_{\text{recup}}$	0.85	0.60	0.95	–
Intercooler Outlet Temperature	T_{IC}	45	25	60	°C
Primary Heat Exchanger Power	Q_{core}	120	–	–	MW
Primary Heat Exchanger Outlet Temp.	$T_{\text{core,out}}$	1200	1100	1300	°C
Pressure Drop per Heat Exchanger	ΔP_{HX}	0.1	0.05	0.15	bar

Note: Air as working fluid (CoolProp). $Q_{\text{core}} = 120$ MW held constant for all configurations.

1.2. Sensitivity Analysis Methodology

The sensitivity analysis employs the variance-based Sobol method to decompose the output variance $V(Y)$ into contributions from individual parameters and their interactions [7, 13]. The first-order index $S_i = V_i/V(Y)$ quantifies the main effect of parameter X_i, while the total-order index S_{T_i} captures the contribution of X_i including all its interactions with other parameters.

The Sobol indices are computed using the Saltelli estimators [14]. Two independent quasi-random matrices A and B of size $N \times k$ are generated, where $N = 1024$ is the number of samples and k the number of input parameters. For each parameter i, a hybrid matrix $A_B^{(i)}$ is built by replacing column i of A with the corresponding column from B. The first-order and total-order indices are then estimated as:

$$S_i \approx \frac{1}{NV(Y)} \sum_{j=1}^{N} f(B)_j \left[f(A_B^{(i)})_j - f(A)_j \right], \tag{1}$$

$$S_{T_i} \approx \frac{1}{2NV(Y)} \sum_{j=1}^{N} \left[f(A)_j - f(A_B^{(i)})_j \right]^2, \tag{2}$$

where $f(\cdot)$ is the model output (P_{net} or η) and $V(Y)$ its variance.

The analysis excludes second-order interactions, requiring $N_{\text{eval}} = N(k+2)$ function calls. Given $N = 1\,024$ and between 6 and 9 parameters per cycle, we perform 8 192 to 11 264 model runs for each output.

The 8 parameters studied could fluctuate around their respective reference value, Table 2 delineates the specific boundaries established for each individual parameter.

In this sensitivity analysis, both the efficiency and the net power output of the system are considered as primary performance indicators. Efficiency is commonly defined as the ratio of useful work to the heat input, namely [15]:

$$\eta = \frac{W_{\text{net}}}{Q_{\text{in}}}, \quad W_{\text{net}} = W_{\text{turbine}} - |W_{\text{compressor}}| \geq 0 \tag{3}$$

and for an idealized Carnot cycle, the maximum efficiency is expressed by

$$\eta_{\text{Carnot}} = 1 - \frac{T_C}{T_H}, \tag{4}$$

where $T_H = T_{\text{core,out}}$ is the primary heat exchanger outlet temperature and $T_C = T_{\text{in}}$ is the compressor inlet temperature, both in Kelvin. The Carnot efficiency serves here as a theoretical upper bound for comparison only

On the other hand, the net power output of the system is given by

$$P_{\text{net}} = P_{\text{turbine}} - P_{\text{compressor}}, \tag{5}$$

where P_{turbine} is the power generated by the turbine and $P_{\text{compressor}}$ is the power consumed by the compressor.

Analyzing both metrics allows us to distinguish between parameters that enhance thermodynamic efficiency and those that increase net power delivery. This approach provides designers with a fuller understanding of the trade-offs inherent in cycle optimization.

2. Results and Discussion

Figure 2 compares the Temperature-Entropy (T-s) trajectories for the five investigated cycle configurations, while Figure 3 quantifies their performance in terms of net work, thermal efficiency, and mass flow rate at reference conditions (Table 2).

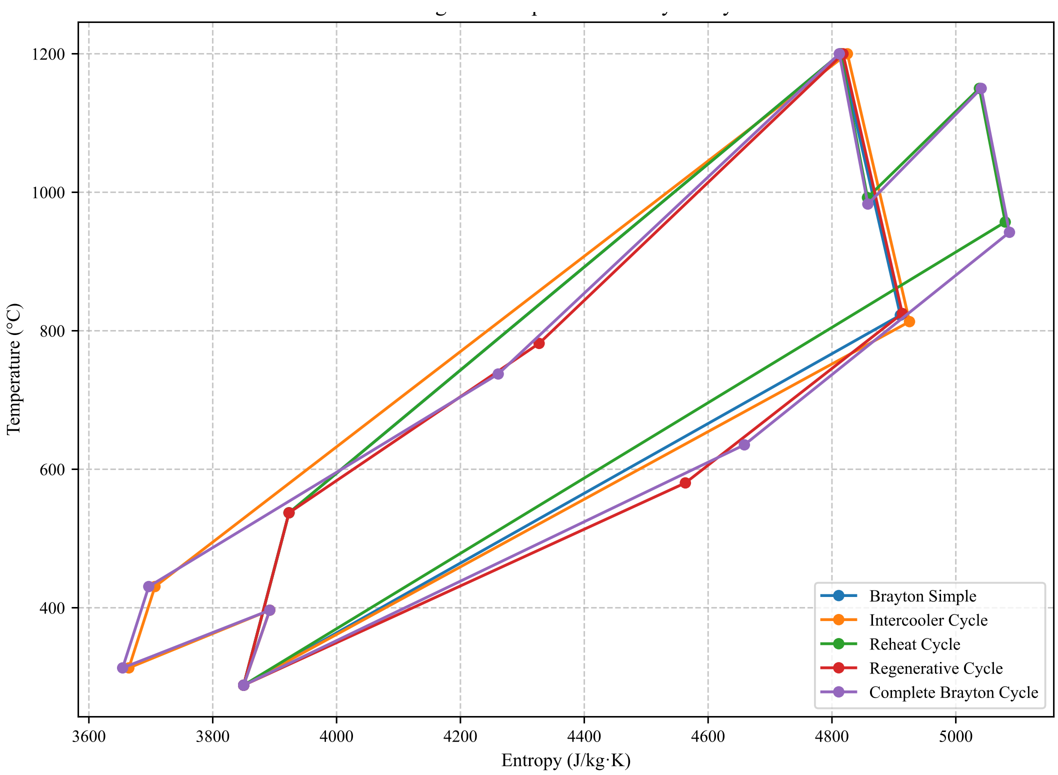

Figure 2 : *Temperature-Entropy diagram comparing the five Brayton cycle configurations. All parameters are set to their reference values given in Table 2.*

The **Simple** cycle serves as the reference case, using standard compression followed by expansion. With an **Intercooler**, the gas is cooled between two compressor stages, lowering the inlet temperature to the second stage. This reduces the energy needed for compression and improves both net work and efficiency slightly, though mass flow decreases for a given primary heat exchanger thermal output ($Q_{\text{core}} = 120$ MW) [16].

The **Reheat** variant injects additional heat mid-expansion, elevating the average heat supply temperature and extracting more work from the turbine. Yet when the peak cycle temperature is held constant, reheat produces the weakest results (Figure 3). Zhao et al. [17] point out that frictional losses in the reheater can cancel out any thermodynamic advantage.

The **Regenerative** cycle recovers waste heat from the turbine exhaust to preheat air entering the primary heat exchanger, reducing thermal input requirements. This yields the highest thermal efficiency among single-modification configurations (Figure 3). The regenerator increases the average heat supply temperature while reducing heat rejection, and is particularly effective when turbine exhaust temperature exceeds compressor discharge temperature [18].

By incorporating intercooling, reheat, and regeneration simultaneously, the **Complete** cycle attains superior performance on both metrics (Figure 3). While this design extracts near-maximum thermodynamic potential from the working fluid [6], it requires more components and control strategies than simpler variants.

Table 3 summarizes the key performance metrics obtained from the thermodynamic simulation:

Figure 4 presents the first-order (S1) and total-order (ST) Sobol indices for both net power output P_{net} and thermal efficiency η across all five Brayton cycle configurations. The sensitivity

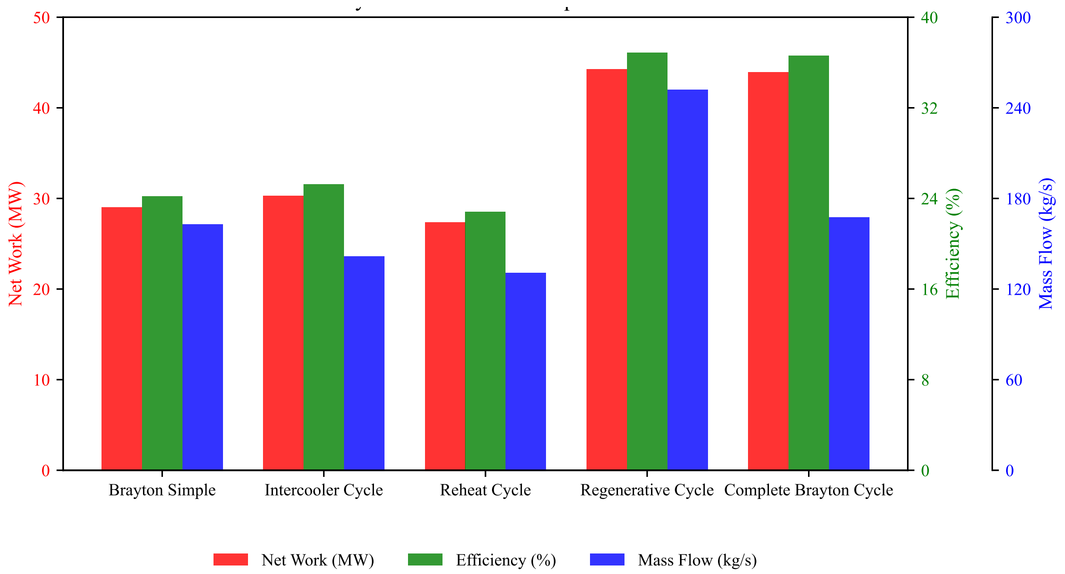

Figure 3 : *Comparison of net work, thermal efficiency, and mass flow rate for the five Brayton cycle configurations at reference conditions (Table 2).*

Table 3 : *Summary of Performance Metrics for the Investigated Brayton Cycle Configurations*

Configuration	**Net Work (MW)**	**Efficiency (%)**	**Mass Flow (kg/s)**
Brayton Simple	29.0	24.2	162.8
Intercooler Cycle	30.3	25.3	141.7
Reheat Cycle	27.4	22.8	130.6
Regenerative Cycle	44.3	36.9	252.1
Complete Brayton Cycle	44.0	36.6	167.4

analysis reveals distinct dominant parameters for each architecture:

For the Simple cycle, turbine efficiency η_{turb} predominates with a Sobol index around 0.6, reflecting the direct impact of turbine performance on net power extraction. The Intercooled cycle exhibits a markedly different behavior, with the compressor pressure ratio π_{comp} emerging as the dominant parameter ($\mathrm{S1} \approx 0.8$), as intercooling amplifies the sensitivity to compression staging. In the Reheat configuration, both turbomachine efficiencies—compressor and turbine—share comparable influence, indicating a balanced sensitivity between compression and expansion processes. The Regenerative cycle displays a more distributed sensitivity pattern: turbine efficiency remains significant (≈ 0.4), while $T_{\text{Prim Heat EXC,out}}$ and compressor efficiency also contribute meaningfully, as the recuperator redistributes energy flows and couples multiple parameters. Finally, the Complete cycle is predominantly governed by turbine efficiency, which emerges as the leading sensitivity driver despite the architectural complexity.

Since Q_{in} is held constant across all cases, the sensitivity of η mirrors that of P_{net} exactly.

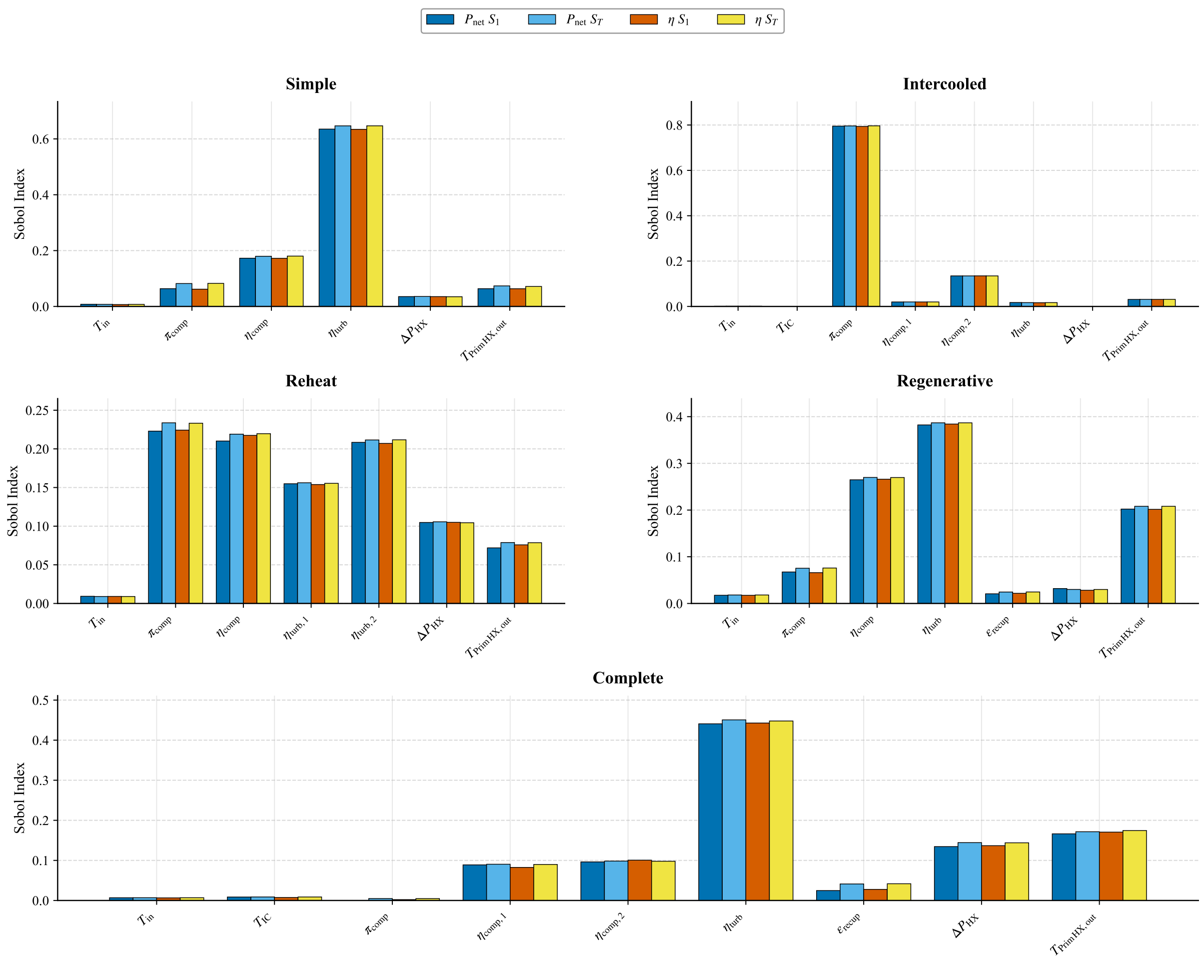

Figure 4 : *Sobol S1 and ST indices for net power P_{net} and efficiency η.*

3. Conclusion

This work presented a comprehensive thermodynamic and Sobol sensitivity analysis of five Brayton cycle configurations: Simple, Intercooled, Reheat, Regenerative, and Complete. The component-level modeling accounted for isentropic efficiencies, pressure ratios, heat exchanger pressure drops, and recuperator effectiveness, enabling detailed evaluation of each configuration's net power output and thermal efficiency under identical heat input conditions. The Sobol analysis revealed that the maximum cycle temperature (turbine inlet temperature) is by far the most influential parameter, followed by compressor and turbine isentropic efficiencies, while pressure ratio and pressure-drop terms showed only moderate impact. These findings confirm that raising the maximum temperature and minimizing irreversibilities are the most effective levers to improve both power output and efficiency.

Holding Q_{in} fixed means that $\eta = P_{\text{net}}/Q_{\text{in}}$ tracks P_{net} directly, yielding identical Sobol indices for both outputs. While both indicators are retained here for cross-study comparability, a single output metric would have been sufficient under this constraint. Relaxing the constant heat-input assumption in future work would decouple efficiency from net power, enabling exploration of trade-offs not captured in the present analysis. When thermal input doesn't change, boosting net output inherently improves efficiency at the same rate. Future studies might relax the constant-heat assumption, examine off-design behavior, or incorporate cost and environmental criteria alongside alternative gases. Accounting for material temperature limits and competing design objectives would sharpen guidance for next-generation systems.

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