

Preliminary Feasibility Assessment of PRDBE-Based Control for Process Heat HTGRs

Nayoung Kim^a, Jeong Ik Lee^{a*}

^aDepartment of Nuclear and Quantum Engineering Korea Advanced Institute of Science and Technology

*Corresponding author: jeongiklee@kaist.ac.kr

***Keywords** : process heat HTGR, PRDBE, control strategy

1. Introduction

Deep decarbonization of industrial sectors requires substantial carbon reductions in high-temperature, steam-based process heat services [1,2]. High-temperature gas-cooled reactors (HTGRs) are graphite-moderated and helium-cooled systems fueled by TRISO particles [3]. They can supply high-grade heat for power generation as well as for industrial process heat and hydrogen production. The High Temperature Engineering Test Reactor (HTTR) demonstrated outlet helium temperatures on the order of 950 °C [5,6]. This capability broadens nuclear applications beyond electricity generation toward process steam supply.

Near-term HTGR concepts for industrial heat typically target a reactor outlet temperature of about 750 °C. This range enables high-quality steam generation while maintaining practical material limits and system design margins. In this study, the rated reactor outlet temperature is set to 750 °C. Heat is delivered to a helical once-through steam generator and downstream process equipment.



Figure 1. HTGR facilities in the world: the HTR-PM in China (left) and the HTTR in Japan (right).

The control problem of a process-heat HTGR cannot be formulated as a direct extension of grid-driven load following in electricity-only plants [7,8]. In power-generation systems, major disturbances are often associated with grid events and turbine load changes, and performance is commonly assessed by electrical load tracking and turbine-inlet steam conditions. In contrast, process-heat operation is governed by steam quality at the nuclear-process interface. Steam temperature and pressure must remain within acceptable limits under demand-side variations. Valve operations and operating-point changes in the industrial plant alter feedwater conditions and steam boundary conditions. These disturbances propagate from the secondary system to the primary system.

Core thermal constraints further tighten the feasible operating space. Graphite can accumulate irradiation-

induced lattice defects, storing latent energy known as Wigner energy. During heating, this stored energy is released as defects anneal. For low-temperature irradiated graphite, a pronounced release peak around 200 °C has been reported [11,12]. Experimental and assessment results also indicate that annealing in the 250–300 °C range removes a substantial fraction of releasable stored energy [13]. Demand-driven overcooling that lowers the primary temperature level can therefore weaken annealing conditions and reduce operating margins from a graphite thermal-management perspective. Based on this consideration, this study treats primary-side overcooling as a limiting condition and enforces a reactor inlet temperature lower bound of 300 °C as a mandatory constraint.

A previous quasi-steady thermal-hydraulic assessment of a 90 MW_{th} process-heat HTGR highlighted a low-load limitation under this constraint set [10]. That assessment fixed the core inlet and outlet temperatures at rated values. In other words, it excluded heat-source temperature adjustment via reactivity control and attempted to meet both constant steam outlet temperature and the reactor inlet temperature lower bound using only secondary-side manipulations. No operating point satisfying both requirements existed in the deep part-load regime. This result implies that, when the heat-source temperature level is held fixed, the achievable thermohydraulic adjustment range of secondary-side actions can become insufficient at low load.

Heat-source temperature adjustment is effectively coupled to reactivity control using control rods. Frequent power adjustments in response to process demand variations can change the temperature histories of the core and major structures. This can increase thermal-cycling management requirements and operational complexity. In addition, actions taken to preserve heat quality in process-heat systems directly affect plant utilization and operating cost. It is therefore desirable to maximize the operating range achievable by secondary-side actions and to introduce heat-source-side actions only when necessary.

From this perspective, this study compares baseline two-variable control using secondary-side manipulations with a three-variable control that adds a primary pressure setpoint adjustment via helium inventory control. The analysis quantifies how the expanded control freedom recovers constraint-satisfying operation at low load and mitigates the required operating trajectory for meeting the same heat-quality targets. Representative demand-side variations are then formulated from an event-

grounded viewpoint [9] and remaining limiting conditions under three-variable control are identified. Under such conditions, the need for additional actuation including heat-source temperature adjustment is assessed in the context of operational constraints.

2. Methods and Results

2.1 System Configuration

The reference system for this study is a 90 MW_{th} prismatic high-temperature gas-cooled reactor (HTGR) coupled to a helical once-through steam generator (OTSG) supplying high-temperature steam to an industrial process heat user via a reboiler and steam distribution system. The thermal and mass balance boundary considered in this analysis excludes the internal dynamic behavior of the downstream chemical process plant and is strictly confined to the primary and secondary systems responsible for heat generation and delivery.

The primary system consists of the reactor core, a helium circulator, and the shell side of the steam generator, in which high-temperature helium flows downward. The secondary system comprises a feedwater pump, a feedwater heater, and the tube-side flow path of the helical OTSG, where the upward flow of the working fluid produces superheated steam. The key design parameters under the rated 100% thermal power condition are summarized in Table 1 below. Under the nominal conditions, the thermal balance between the two systems is inherently satisfied, such that the prescribed reactor inlet temperature and steam outlet temperature are simultaneously achieved.

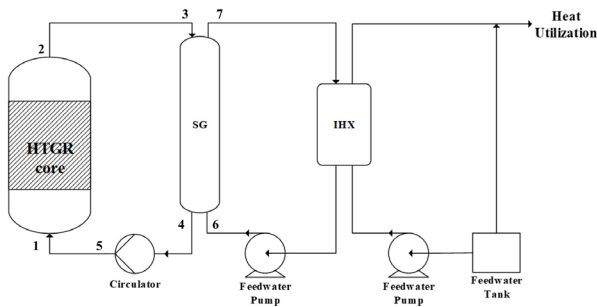


Figure 2. Diagram of Process Heat HTGR system.

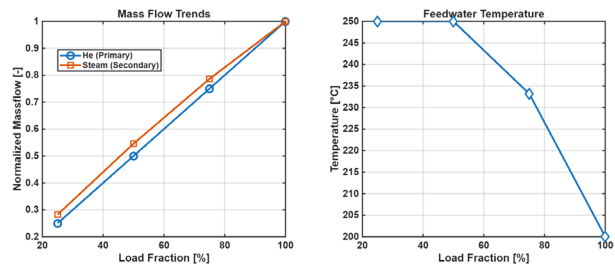
Table 1. Nominal operating conditions at 100% rated thermal power

System	Parameter	Value
Primary System	Operating Pressure	6.4 MPa
	Reactor Inlet Temp	300 °C
	Reactor Outlet Temp	750 °C
Secondary System	Feedwater Supply Pressure	21 MPa
	SG Inlet Feedwater Temp	200 °C
	Process Steam Outlet Temp	575.1 °C

2.2 Quasi-steady Multivariable Control Strategies

When the process-heat HTGR system is reduced from rated power to deep part load, a thermodynamic imbalance can arise because the OTSG conductance is largely fixed by geometry whereas the primary and secondary heat-capacity rates decrease with load, rendering the steam generator effectively over-sized at reduced mass flow. To examine quasi-steady feasibility under different actuator allocations, four control modes were defined with feedwater flow as a common manipulated variable and a second manipulated variable selected on either the secondary side or the primary side. System states are reported using seven nodal temperatures (Nodes 1–7), as indicated in Figure 2.

The quasi-steady results reveal mode-dependent feasibility limits. Mode 1 maintains steam conditions by secondary pressure adjustment, but the low-load solution is driven close to the water critical pressure (≈ 21.6 MPa) and still violates the 300 °C reactor-inlet requirement at 25% load. Mode 2 uses feedwater inlet temperature as the second degree of freedom; however, the practical heater bound (200–250 °C) becomes active at 50% load and below, preventing simultaneous satisfaction of the reactor-inlet and steam-outlet targets. Mode 3 adjusts primary pressure via helium inventory control, yet under the fixed reactor-outlet-temperature assumption pressure reduction provides limited thermal leverage, so reactor-inlet recovery remains insufficient despite stable steam outlet conditions. Mode 4 directly manipulates reactor outlet temperature and satisfies both targets over 25–100% load but requires a wide outlet-temperature range (≈ 585 –750 °C), implying increased thermal-cycling burden and an expanded off-design envelope. Across the mode-to-mode comparison, Mode 2 provides the most practical baseline because feedwater temperature actuation is directly implementable via conventional feedwater-heater operation, while alternative modes either approach near-critical secondary pressure (Mode 1), require large reactor-outlet temperature swings (Mode 4), or provide limited low-load recovery under fixed outlet temperature (Mode 3). On this basis, Mode 2 is augmented with helium-inventory-based primary pressure setpoint adjustment to evaluate the mitigation achieved by the resulting three-variable control allocation.



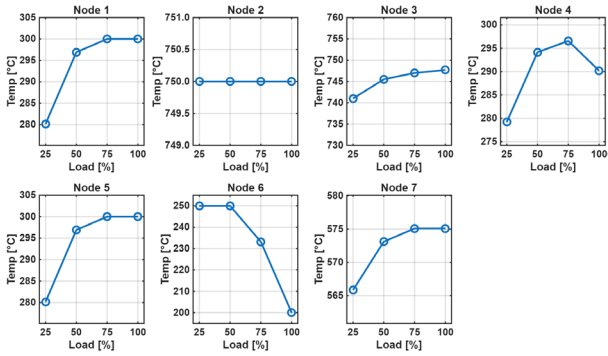


Figure 3. [Mode 2] Nodal temperatures by load, flow rate, and feedwater temperature.

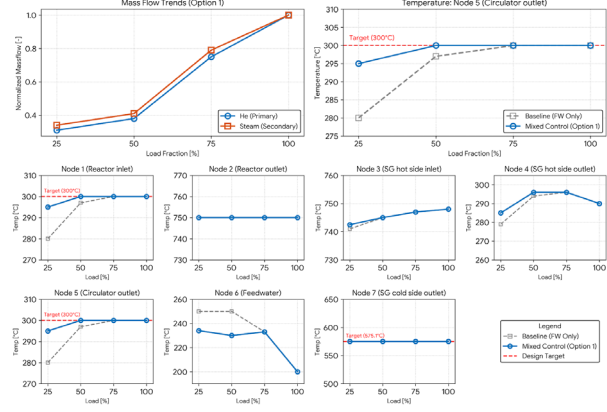


Figure 6. [Option 1] Nodal temperatures by load, flow rate, and primary temperature

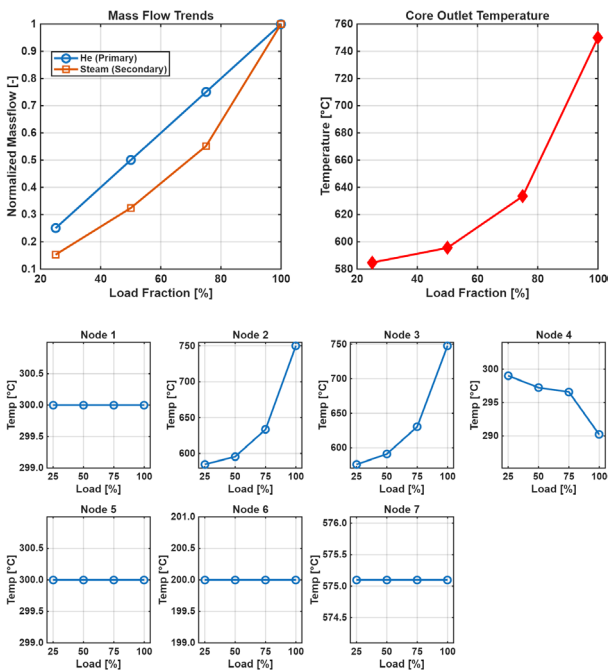


Figure 4. [Mode 4] Nodal temperatures by load, flow rate, and primary temperature.

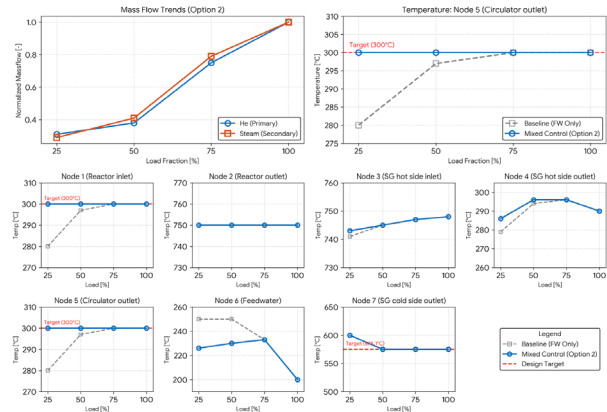


Figure 7. [Option 2] Nodal temperatures by load, flow rate, and primary temperature

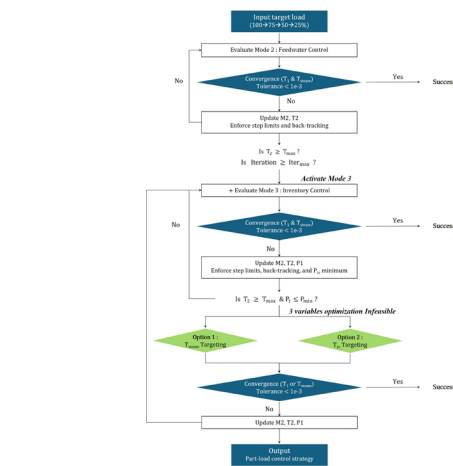


Figure 5. Algorithm diagram of Advanced control strategy

2.3 Mitigation Logic with Helium Inventory Control

To examine whether the low-load infeasibility of the Mode 2 baseline can be mitigated without direct reactor-outlet-temperature manipulation, a hierarchical search logic was introduced by augmenting the secondary-side baseline with helium-inventory-based primary pressure adjustment. In the initial stage, Mode 2 is applied using feedwater flow and feedwater inlet temperature as the manipulated variables. The solution is iteratively updated to satisfy the reactor inlet temperature and process steam outlet temperature targets under the practical feedwater-heater constraint.

If the Mode 2 search does not converge before the feedwater inlet temperature reaches its upper bound or the iteration limit is exceeded, the algorithm activates Mode 3 by introducing primary pressure adjustment as an additional degree of freedom. In this extended stage, feedwater flow, feedwater inlet temperature, and primary pressure are updated together. This step evaluates whether limited primary-side flexibility can recover a feasible operating point while maintaining the fixed reactor-outlet-temperature assumption.

Figure 5 summarizes the hierarchical feasibility search and fallback logic adopted in this study. For each target load, the solution is first sought using Mode 2. When the baseline search fails due to activation of the feedwater temperature limit or non-convergence, the search is extended to the three-variable allocation. If the three-variable search also fails to satisfy both thermal targets under the simultaneous activation of the feedwater temperature upper bound and the minimum allowable primary pressure constraint, the operating condition is treated as infeasible for full target recovery.

In such cases, the algorithm switches to a fallback search based on reduced objectives. Two alternatives are considered: one prioritizes the process steam outlet temperature, and the other prioritizes the reactor inlet temperature. This fallback structure is introduced not to redefine the main control target, but to identify an admissible operating point when simultaneous recovery of both targets is not achievable within the available actuation range.

The extended control allocation improves operational flexibility but does not fully eliminate the low-load feasibility limitation. Once the feedwater-heater upper bound becomes active, the additional freedom provided by primary pressure adjustment can partially relieve the thermal imbalance. For example, at 25% load, the reactor inlet temperature under the baseline control drops to approximately 280 °C, whereas the mixed control recovers it to 300 °C, corresponding to an improvement of about 20 °C. At 50% load, an additional recovery of about 2 °C is observed relative to the baseline. The extent of this mitigation, however, depends on the selected fallback objective. In Option 1, the process steam outlet temperature remains close to the design target over the full load range while the reactor inlet temperature is recovered. In Option 2, greater priority is assigned to reactor inlet temperature recovery, which leads to a larger deviation of the steam outlet temperature at 25% load. These results show that the added primary pressure adjustment provides a meaningful mitigation effect in the deep part-load region, but under the fixed reactor-outlet-temperature assumption the simultaneous recovery of both thermal targets remains limited.

In the present system, the Mode 2 baseline is primarily limited by a practical actuator bound, whereas the three-variable extension remains limited by weak thermodynamic leverage under the imposed operating assumptions. By contrast, direct manipulation of reactor outlet temperature can recover both the reactor inlet target and the process steam outlet target across the full load range, but only by substantially widening the reactor thermal operating envelope. The present analysis therefore shows that the low-load problem is governed by feasibility limits associated with actuator bounds and component-level thermodynamic mismatch.

3. Conclusions

This study investigated the quasi-steady part-load feasibility of a 90 MWth process-heat HTGR coupled to a helical once-through steam generator under simultaneous steam-quality requirements and primary-side thermal protection constraints. The results show that the baseline secondary-side control based on feedwater flow and feedwater inlet temperature cannot simultaneously satisfy the reactor inlet temperature target and the process steam outlet temperature target in the low-load region once the feedwater-heater upper bound is reached. To mitigate this limitation, a three-variable control allocation was introduced by adding helium-inventory-based primary pressure adjustment. The extended control improved reactor inlet temperature recovery in the deep part-load region; for example, at 25% load, an improvement of about 20 °C was obtained relative to the baseline control, and additional recovery was also observed at 50% load. However, under the fixed reactor-outlet-temperature assumption, the thermal leverage provided by pressure variation remains limited, so a fully constraint-satisfying solution for simultaneous recovery of both thermal targets cannot be guaranteed over the full operating range. These results indicate that the low-load problem is governed not simply by controller tuning, but by feasibility limits associated with actuator bounds and component-level thermodynamic mismatch. The present quasi-steady results also suggest that feedwater temperature constitutes a representative disturbance pathway through which process-side variations are imposed on the system as secondary-side condition changes. On this basis, PRDBE-oriented transient verification under representative process-origin disturbances will be addressed in future work.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2024-00457356).

REFERENCES

- [1] IPCC. (2022) “AR6 WGIII Chapter 11: Industry.” Intergovernmental Panel on Climate Change (IPCC).
- [2] International Energy Agency. (2025) “Renewables 2025: Renewable heat.” IEA.
- [3] OECD Nuclear Energy Agency. (2022) “High-temperature gas-cooled reactors and industrial heat applications.” OECD-NEA.
- [4] IAEA. (2010) “High Temperature Gas Cooled Reactor Fuels and Materials.” IAEA-TECDOC-1645.
- [5] Japan Atomic Energy Agency. (n.d.) “Outline of High Temperature Engineering Test Reactor (HTTR).” JAEA.
- [6] Fujikawa, S. (2004) “Achievement of Reactor-Outlet Coolant Temperature of 950°C in HTTR.” *Journal of Nuclear Science and Technology*.
- [7] Jiang, D., Dong, Z., Zhu, Y., Yu, H., Huang, X. (2025) “Coordinated control of the World’s first multi-modular high temperature gas-cooled reactor power plant HTR-

PM.” Nuclear Engineering and Technology.
[8] Wu, Q., Qiu, S., Lei, J., Su, Z. (2023) “A load following control strategy for Chinese modular high temperature gas cooled reactor.” Energy Conversion and Management 281, 116085.

[9] Holbrook, M. (2010) “Next Generation Nuclear Plant Licensing Basis Event Selection White Paper.” Idaho National Laboratory, INL/EXT-10-19521.

[10] U.S. NRC. (2020) “Regulatory Guide 1.233: Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to inform the licensing basis and content of applications for licenses, certifications, and approvals for non-light-water reactors” U.S. Nuclear Regulatory Commission.