

Preliminary Screening of Thermal-Hydraulic Phenomena for HECTAR at Rated-Power Operation Based on Existing HTGR PIRTs

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1. Introduction

A high-temperature gas-cooled reactor (HTGR) uses helium as the coolant and graphite as the moderator and structural material. Their high coolant outlet temperatures make them suitable not only for electricity generation but also for industrial process heat applications. In the Republic of Korea, the Helium Cooled Thermal Application Reactor (HECTAR), a prismatic HTGR intended for industrial process heat supply, is under development.

Safety assessment of a new reactor requires the modeling of major systems and components using safety analysis codes and the prediction of their thermal-hydraulic behavior under normal operating and accident conditions. For HECTAR, an analysis framework based on GAMMA+, a thermal-fluid and accident analysis code for HTGRs, needs to be established. This requires identifying relevant thermal-hydraulic phenomena and examining whether the analysis models can adequately represent them.

A Phenomena Identification and Ranking Table (PIRT) is a methodology for systematically identifying phenomena relevant to a particular reactor and scenario and evaluating their importance levels (ILs) and knowledge levels (KLs). PIRT results can provide a technical basis for assessing the applicability of safety analysis codes, identifying model validation needs, and prioritizing the acquisition of experimental data [1–3].

A thermal-hydraulic PIRT for HECTAR should be developed progressively, covering normal operation as well as a range of transient and accident conditions. Understanding the basic behavior of major systems and thermal-hydraulic regions under a reference operating condition is a prerequisite for evaluating their response to accidents. During 100% rated-power operation, heat generated in the core is transferred by primary helium through the Heat Transport System (HTS) and removed on the secondary side of the steam generator. Heat transferred through the outer surface of the reactor pressure vessel (RPV) is removed through the reactor cavity and the Reactor Cavity Cooling System (RCCS).

In this study, 100% rated-power operation was selected as the reference condition for HECTAR. Existing HTGR PIRTs developed by KAERI/ANL, the NRC, and KINS were reviewed to preliminarily

screen candidate phenomena applicable to the major HECTAR systems and thermal-hydraulic regions. The existing IL and KL assessments were also compared to compile preliminary screening results. Where directly corresponding information was limited, the candidate phenomena were supplemented by considering the design characteristics of HECTAR systems and components.

The objective of this study is not to determine the final ILs and KLs for HECTAR, but to systematically organize the thermal-hydraulic phenomena relevant to rated-power operation and the corresponding assessments from existing PIRTs. The results are intended to provide a basis for future HECTAR-specific PIRT development and analysis model review.

2. Methodology for Preliminary Screening

Existing HTGR PIRTs developed by KAERI/ANL [1], the NRC [2], and KINS [3] were reviewed to identify thermal-hydraulic phenomena relevant to HECTAR rated-power operation. The NRC and KINS studies were examined primarily for phenomena associated with normal operation, while phenomena considered under normal-power and load-change conditions were also referenced from the KAERI/ANL study.

Because the reference reactor designs, system configurations, and classification schemes differ among the existing PIRTs, the listed phenomena were not directly transferred to HECTAR. In particular, the NRC PIRT is organized around major thermal-fluid issues rather than individual component-level phenomena. The physical meaning of each issue was therefore examined and compared with the classifications used by KAERI/ANL and KINS to map it to the corresponding thermal-hydraulic region in HECTAR.

Candidate phenomena were screened from the existing HTGR PIRTs based on their relevance to the HECTAR system configuration and normal operating conditions. Where the reference reactor design differed from HECTAR, the physical meaning of each phenomenon and its applicability to HECTAR were considered. Phenomena needed to understand the basic thermal-hydraulic behavior at rated power or the initial conditions for subsequent accident analyses were retained. In contrast, phenomena associated

exclusively with specific accident conditions, such as pressure-boundary breaks or air ingress, were excluded from the screening scope.

The power conversion unit (PCU) and intermediate heat exchanger (IHX) included in some reference PIRTs were excluded because they are not part of the current HECTAR design. The shutdown cooling system (SCS) was not considered separately because its operation falls outside the scope of 100% rated-power operation examined in this study.

The thermal-hydraulic regions of HECTAR were defined according to its major system configurations and the coolant-flow and heat-transfer paths under normal operation. The Reactor System was divided into the Active Core & Reflectors, Helium Inlet Flow Path, Upper Plenum, and Lower Plenum. The Heat Transport System comprises the Cross Vessel, Steam Generator, and Helium Circulator. The Reactor Cavity and the heat-removal path of the water-cooled RCCS were considered within the Reactor Cavity Cooling System. Fig. 1 illustrates the overall system configuration of HECTAR and the principal flow paths during rated-power operation.

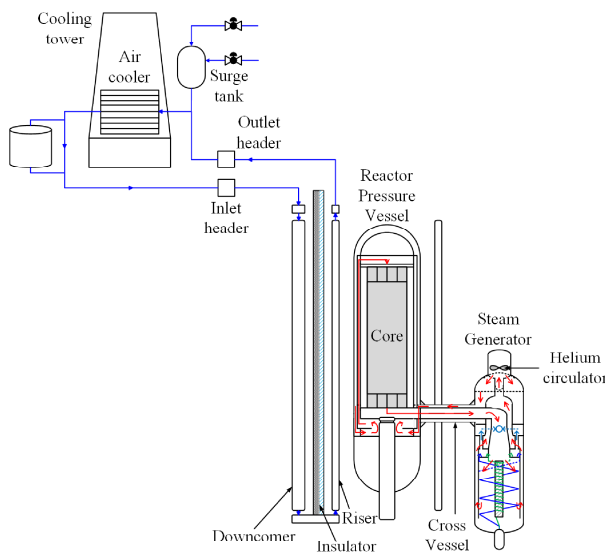


Fig. 1. Schematic of the HECTAR system configuration and principal coolant-flow paths under rated-power operation.

Under normal operation, primary helium is circulated by the Helium Circulator and distributed to the core through the Helium Inlet Flow Path and Upper Plenum. Helium heated in the core is collected in the Lower Plenum, flows through the Hot Gas Duct inside the Cross Vessel to the Steam Generator, transfers heat to the secondary side, and returns to the Helium Circulator. Meanwhile, heat transferred through the RPV outer wall is removed through the Reactor Cavity and RCCS to the ultimate heat sink. Candidate thermal-hydraulic phenomena were organized according to these flow and heat-transfer paths.

RCCS configurations are generally classified as air-cooled or water-cooled, and HECTAR adopts a water-cooled system. In the existing HTGR PIRTs reviewed, including KAERI/ANL, directly corresponding assessment results for a water-cooled RCCS under normal-power and load-change (LC) conditions were difficult to identify. Accordingly, phenomena in the Reactor Cavity were screened with reference to the existing PIRTs, whereas candidate phenomena associated with coolant circulation and external heat removal in the water-cooled RCCS were identified separately based on the HECTAR system configuration. Candidate phenomena for the Steam Generator and Helium Circulator were also compiled separately, considering differences from the reference designs and the current level of design definition for HECTAR.

The IL and KL values reported in existing PIRTs were used as reference information for preliminary screening rather than as final HECTAR-specific rankings. Where corresponding assessments were available from multiple PIRTs, the highest reported IL and the lowest reported KL were adopted as the Screening Result. No separate rankings were assigned to HECTAR-related phenomena for which directly corresponding assessment information was unavailable.

3. Screening Results for Rated-Power Operation

Table I presents the candidate phenomena screened for HECTAR at 100% rated-power operation and the corresponding assessments from existing HTGR PIRTs.

3.1. Reactor System

In the Reactor System, thermal-hydraulic phenomena were considered in the Active Core & Reflectors, Helium Inlet Flow Path, Upper Plenum, and Lower Plenum. In the Active Core & Reflectors, coolant flow distribution and bypass flow, forced- and mixed/free-convection heat transfer, and flow-path pressure losses occur. The thermal properties of the fuel and graphite, multidimensional heat conduction, gas conduction across gaps, and radiative heat transfer also influence core thermal behavior. Power distribution, stored energy, decay heat, and reactivity feedback are additionally associated with core heat generation and temperature behavior.

In the Helium Inlet Flow Path, helium flow distribution, forced-convection heat transfer, and pressure losses occur; local mixed/free convection, thermal stratification, gas conduction, and radiative heat transfer may also be relevant. In the Upper Plenum, incoming helium is redistributed and undergoes thermal mixing and stratification. Multidimensional conduction and radiative heat transfer in surrounding structures, together with the

Table I. Preliminary Screening Results for HECTAR at Rated-Power Operation.

Systems	Components	Phenomena	KAERI/ANL	NRC [2]		KINS [3]		Screening Result	
			IL	IL	KL	IL	KL	IL	KL
Reactor System	Active Core & Reflectors	flow distribution (including bypass flow)	H	H	L	H	L	H	L
		heat transfer (forced convection)	H	M	M			H	M
		heat transfer (mixed and free convection)							
		pressure drop (forced convection)	H	H	M	H	H	H	M
		pressure drop (mixed and free convection)							
		Initial stored energy				H	M	H	M
		power distribution	H					H	
		decay heat (including power distribution)		H	M	H	M	H	M
		reactivity feedback	H	H	M			H	M
		fuel/reflector conductivity	M	H	M	H	M	H	M
		fuel/reflector specific heat	M	H	M	H	M	H	M
		multi-D heat conduction including contact	M	M	H	H	M	H	M
		gas conduction (including gaps)		M	H	H	H	H	H
		radiation heat transfer		M	H	H	M	H	M
		fluid properties (gas mixture)				H	M	H	M
	Helium Inlet Flow Path	flow distribution	H	M	M	H	M	H	M
		heat transfer (forced convection)		M	M	H	H	H	M
		heat transfer (mixed and free convection)							
		pressure drop (forced convection)	H	H	M	L	M	H	M
		pressure drop (mixed and free convection)							
		fluid properties (gas mixture)							
		thermal mixing and stratification							
		gas conduction (including gaps)							
		radiation heat transfer							
	Upper Plenum	flow distribution	H	H	M			H	M
		heat transfer (forced convection)		M	M	L	M	M	M
		heat transfer (mixed and free convection)							
		pressure drop (forced convection)	H	H	M	H	M	H	M
		pressure drop (mixed and free convection)							
		multi-D heat conduction including contact				M	H	M	H
		radiation heat transfer							
		fluid properties (gas mixture)				M	M	M	M
	Lower Plenum	thermal mixing and stratification		H	L	M	M	H	L
		thermal resistance/heat capacity of shroud							
		flow distribution	H	H	M			H	M
		heat transfer (forced convection)	H	M	M	H	M	H	M
		heat transfer (mixed and free convection)							
		pressure drop (forced convection)	H	H	M	H	H	H	M
		pressure drop (mixed and free convection)							
		multi-D heat conduction including contact				H	M	H	M
		jet discharge	H	H	M	H	H	H	M
		thermal striping	H	H	M			H	M
		fluid properties (gas mixture)				M	H	M	H
		thermal mixing and stratification							
		thermal resistance/heat capacity of shroud							
Heat Transport System	Cross Vessel	heat transfer (forced convection)	H	M	M			H	M
		heat transfer (mixed and free convection)							
		pressure drop (forced convection)		H	M	M	M	H	M
		pressure drop (mixed and free convection)							
		jet discharge		H	M	M	H	H	M
		radiation heat transfer				H	M	H	M
		fluid properties (gas mixture)				H	M	H	M
		pipe/insulator conduction	M					M	
	Steam Generator	Primary-side Forced Convection & Heat Transfer							
		Primary-side Pressure Drop							
		Boiling / Two-phase Heat Transfer on Secondary-side							
		Flow Maldistribution & Temperature Non-uniformity							
	Helium Circulator	Pump/Blower Performance vs System Resistance							
		Internal Flow & Efficiency							
		Performance Variation with Temperature/Density							
		Flow Fluctuation / Vibration Coupling							
Reactor Cavity Cooling System	Reactor Cavity	flow distribution				M	M	M	M
		heat transfer (mixed and free convection)		M	M	H	M	H	M
		pressure drop (mixed and free convection)							
		radiation heat transfer		M	M			M	M
		multi-D heat conduction including contact		M	H	M	M	M	M
		thermal striping				M	H	M	H
		gas conduction (including gaps)		M	M			M	M
		conduction to ground				L	M	L	M
		fluid properties (gas mixture)							
	Reactor Cavity Cooling System	water-side natural circulation							
		flow distribution among parallel paths							
		single-phase pressure drop							
		Air Cooler heat transfer							
		Cooling Tower natural draft / chimney effect							

Note: H, M, and L denote High, Medium, and Low Importance Level (IL) or Knowledge Level (KL), respectively. The Screening Result was conservatively derived from the reviewed HTGR PIRTs by adopting the highest available IL and the lowest available KL. The resulting values are reference-based preliminary screening results and do not represent final HECTAR-specific rankings. A blank entry indicates that no directly corresponding IL/KL evaluation was identified in the reviewed PIRT sources and does not imply that the phenomenon is absent or of low importance in HECTAR.

thermal resistance and heat capacity of the shroud, may influence plenum thermal behavior.

In the Lower Plenum, high-temperature helium jets discharged from individual core channels merge, potentially producing jet-discharge behavior, thermal mixing, and thermal striping. Flow distribution, forced-convection heat transfer, pressure losses, and multidimensional conduction in surrounding structures also affect the temperature and flow distributions in this region.

3.2 Heat Transport System

The Heat Transport System comprises the Cross Vessel, Steam Generator, and Helium Circulator and transfers heat carried by primary helium. In the Cross Vessel, helium undergoes forced-convection heat transfer and pressure losses, while mixed/free-convection effects may arise depending on the flow conditions. Radiative heat transfer involving surrounding structures, along with conduction through the duct and insulation, also influences its thermal behavior.

In the Steam Generator, forced-convection heat transfer and pressure losses occur on the primary helium side, while boiling and two-phase heat transfer take place on the secondary side as heat is absorbed from the primary coolant. Flow maldistribution and temperature nonuniformity may develop as the fluid is distributed among multiple heat-transfer tubes.

In the Helium Circulator, primary-system flow is established by the relationship between circulator performance and system resistance. Internal flow and efficiency, performance variations with helium temperature and density, and the coupling between flow fluctuations and vibration may affect rated-power operating characteristics.

3.3. Reactor Cavity Cooling System

In the Reactor Cavity Cooling System, heat transferred from the RPV to the Reactor Cavity and water-cooled RCCS is removed to the ultimate heat sink.

Within the Reactor Cavity, radiative heat transfer between the RPV and surrounding structures and mixed/free convection of the cavity gas occur. Flow distribution, multidimensional heat conduction in structures, gas conduction across gaps, and heat conduction to the ground may also influence the cavity thermal behavior.

In the water-cooled RCCS of HECTAR, density differences in the heated coolant drive natural circulation, while flow distribution among parallel paths and single-phase pressure losses affect system

flow behavior. Heat transported by the RCCS is rejected to air through the Air Cooler and ultimately to the atmosphere by natural draft and the chimney effect in the Cooling Tower.

4. Conclusions

This study preliminarily screened thermal-hydraulic phenomena for HECTAR at 100% rated-power operation by reviewing existing HTGR PIRTs and the configurations of HECTAR systems and components. The IL and KL assessments reported in the reference PIRTs were used to compile preliminary screening results. Candidate phenomena for the Steam Generator, Helium Circulator, and water-cooled RCCS were supplemented based on HECTAR design characteristics where directly corresponding reference information was limited. The Screening Results do not represent final HECTAR-specific ILs or KLs; the phenomena list and rankings will require further refinement through expert evaluation during subsequent HECTAR-specific PIRT development. The present results provide a basis for future HECTAR thermal-hydraulic PIRT development and analysis model review.

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