A Review on the VHTR PIRT Development Status of Both Regulatory Authority and Licensee

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1. Introduction

The VHTR (Very High Temperature Reactor) is defined as a helium-cooled, graphite moderated reactor with a core outlet temperature in excess of 900°C and a long-term goal of achieving an outlet temperature of 1000°C. The VHTR is suited for a broad range of applications, including the production of hydrogen and electricity.

The PIRT (Phenomena Identification and Ranking Table) provides a structured means of identifying and analyzing a wide variety of off-normal sequences that potentially challenge the viability of complex technological systems. As applied to VHTR, the PIRT is used to identify a spectrum of safety-related sequences or phenomena that could affect those systems, and to rank order those sequences on the basis of their frequencies, their potential consequences, and state of knowledge related to associate phenomena. It is to be used as an early screening tool to identify, categorize, and characterize phenomena and issues that are potentially important to risk and safety of VHTR.

Since a specific design has not yet been selected for the choice of the US VHTR (NGNP), it was decided early on to focus on a generic plant and reactor design with broadly typical features. Both a generic Pebble Bed Reactor (PBR) design and a generic Prismatic Modular Reactor (PMR) design were selected as the reference plant for KAERI and ANL PIRT [1, 2]. The generic PBR design selected is a version of the 400 MWt South African PBMR design. The generic PMR design selected is a version of the 600 MWt GT-MHR.

The reference plant of NRC PIRT [3] is assumed to be a modular high temperature gas-cooled reactor (HTGR), either a gas-turbine modular helium reactor (GT-MHR) version (a prismatic-core modular reactor-PMR) or a pebble bed modular reactor (PBMR) version (a pebble bed reactor-PBR) design, with either a direct- or indirect-cycle gas turbine (Brayton cycle) system for electric power production, and an indirect-cycle component for hydrogen production.

The difference of VHTR PIRT characteristics among NRC, KAERI and ANL will be reviewed here. The typical shape for each PIRT is shown in Figure 1.

2. Review on the Characteristics of NRC, KAERI, and ANL PIRTs

2.1 Event Sequences

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[2]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.	H	FOM—upper vessel support, vessel. >Important to control rod drive (CRD) motor and other upper internal structures, thermal stresses.	M*	>Plumes driven by configuration of core, flow function of time; cannot calculate distributions as function of time, need experimental data. >Coupled problem between core and top plenum. >Turbulence modeling.

(a) NRC PIRT Example

Phenomena	HPCC		LPCC			LC	
	1	2	1	2	3	1	2
flow distribution	o	o	o		o	o	o
heat transfer (forced convection)	o		o				

(b) KAERI PIRT Example

Phenomena	Water Ingress		Rod Withdrawal ATWS			H_2 Plant Upset	
	1	2	1	2	3	1	2
Water Vapor Partial Pressure	H	H					
Mass and Energy Loss through Relief Valve	H	H					

(c) ANL PIRT Example

Figure 1 Examples of NRC, KAERI and ANL PIRTs

The event sequences of KAERI PIRT consist of High Pressure Conduction Cooldown (HPCC), Low Pressure Conduction Cooldown (LPCC), and Load Change (LC). The event sequences of ANL PIRT consist of Water Ingress, Rod Withdrawal ATWS (Anticipated Transient Without Scram), and Hydrogen Plant Upset. On the other hand, the event sequences of NRC PIRT consist of Normal operation, General LOFC (Loss Of Forced Circulation), Pressurized LOFC, Depressurized LOFC, Air ingress LOFC, Reactivity (ATWS), and IHX failure (molten salt). Although there are some differences in the event sequences between NRC and KAERI/ANL, the event sequences except for water ingress can be matched with each other.

For the event sequence of water ingress, steam in-leakage from a high-pressure SG would be a dominant risk factor. Otherwise, primary water-cooled heat exchanger secondary systems (in Brayton cycle designs) would run at lower operating pressures and present minimal risks of any substantial water-steam ingress. And NGNP design options with a high-pressure steam generator (Rankine cycle) in the primary loop are not considered in NRC PIRT. Hence, water ingress was eliminated from current NRC PIRT.

2.2 System/Component Classification in PIRT

Conventionally, the PIRT for each event sequence is divided by system/component categories. Table 1 shows system/component classification of KAERI/ANL PIRT. The structure of NRC PIRT is different with KAERI/ANL PIRT as shown in Figure 1. The column "Issue" of NRC PIRT contains the phenomena and system/component information together and doesn't distinguish the system/component separately.

Table 1 System/Component Classification

System	Component
Reactor Vessel	Inlet Plenum
	Riser
	Top Plenum and Components
	Core & Reflectors
	Outlet Plenum and Components
	Lower Head
	Pressure Boundary
Reactor Coolant Loop	Hot/Cold Pipe
	Compressor (Direct) or Circulator (Indirect)
	Intermediate Heat Exchange and Circulator
	Mixing Junction (US VHTR)
Shutdown Cooling System	Heat Exchanger and Pump
RCCS	Reactor Cavity (Confinement)
	RCCS Tube (Air Duct)
	RCCS Piping, Air Cooler and Chimney

Table 2 KAERI/ANL Sequence Phase and Safety Criteria

Event	Phase	Safety Criteria
High Pressure Conduction Cooldown	1: Coastdown	Fuel & Vessel Temperature
	2: Conduction Cooldown	
Low Pressure Conduction Cooldown	1: Blowdown	Fuel & Vessel Temperature
	2: Air Ingress	
	3: Natural Convection	
Load Change	1: Flow Reduction	Local Hot Spot
	2: New Steady State	
Water ingress	1: Pre Turbomachine-Trip	Peak Fuel Temperature Peak Vessel Temperature Confinement Radiation Limits
	2: Post Turbomachine-Trip	
Rod Withdrawal ATWS	1: Pre Turbomachine-Trip	Peak Fuel Temperature Vessel Wall Temperature
	2: Coastdown	
	3: Post Turbomachine-Trip Equilibrium	
Hydrogen Plant Upset	1: Pre Protection-System Trip	Core Outlet Temperature Vessel Pressure
	2: Post Protection-System Trip	

2.3 Sequence Phase and Safety Criteria

KAERI/ANL PIRT evaluates the importance level by dividing sequence phase as shown in Figure 1. The safety criteria, which supply the basis for the determination of importance level, are shown in Table 2. But in NRC PIRT, sequence phase is not divided for each event sequence. And NRC PIRT supplies more detailed safety criteria compared with KAERI/ANL PIRT as shown in Table 3.

2.4 Knowledge Level Ranks

Knowledge level and its rationale are supplied in NRC PIRT, but that isn't in KAERI/ANL PIRT. It is described in KAERI report that knowledge level ranking will be carried out later, when the existing experimental and analytical databases will be surveyed and evaluated.

Table 3 NRC Safety Criteria

PIRT	FOM (Figure of Merit)
Normal operation	- fuel time at temperature - fuel failure fraction - core support structures - time at temperature - vessel and vessel supports temperature - RCCS cavity temperature - primary system boundary integrity - dose to worker/public
General LOFC	- fuel failure fraction - limit vessel temperature - vessel and vessel support integrity - maintain coolable geometry - vessel support temperatures - concrete temperature
Pressurized LOFC	- vessel support temperatures - concrete temperature - fuel temperature - upper vessel support, vessel - damage to SCS HX - pressure boundary failure
Depressurized LOFC	- dose - peak fuel temperature - structural integrity of RCCS - failure of additional pipes
Air ingress LOFC	- fuel temperature - fuel and structural damage - fuel failure fraction - core, concrete integrity - core, core support structure - reactor vessel support - dose to public - Cavity temperature and pressure - RCCS integrity - vessel support, vessel temperature
Reactivity (ATWS)	- fuel failure fraction - corrosion of core supports - dose to public - core support
IHX failure (molten salt)	- public and worker dose - vessel, vessel support, and core support temperatures

3. Conclusion

NRC PIRT doesn't include the detailed phase of event sequence and system/component. And KAERI/ANL PIRT doesn't evaluate knowledge level. The new VHTR PIRT will be developed to obtain the completed PIRT shape by complementing the weakness of the PIRT of NRC, KAERI, and ANL.

REFERENCES

[1] NUREG/CR-6944, Vol. 2, Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs) Volume 2: Accident and Thermal Fluids Analysis PIRTs, March, 2008.
[2] KAERI/TR-3050/2005, Generation of a Preliminary PIRT for Very High Temperature Gas-Cooled Reactors, September, 2005.
[3] ANL-GenIV-071, Prioritization of VHTR System Modeling Needs Based on Phenomena Identification, Ranking and Sensitivity Studies, April 2006.