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Phenomena Identification and Ranking Tables (PIRTs) for a LOCA in Research Reactors

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1. Introduction

Safety and Performance Analyzing CodE (SPACE) [1] is a system thermal hydraulic code developed for the safety and performance analysis of domestic nuclear power plants (NPPs). KAERI has a plan to utilize the SPACE code for the safety and performance analysis of research reactor (RR).

To extend the SPACE code to apply to research reactors, it is very necessary to verify and validate SPACE code against design and operating conditions of RRs since research reactor designs are generally different from NPP and RRs are operating at very low temperature and low pressure conditions.

One of cornerstones for verification and validation of the code is the Phenomena Identification and Ranking Tables (PIRT) which defines the important phenomena in transients and measures understanding of the phenomena.

A series of PIRTs was developed for the postulated initiating events of RRs [2]. In this paper, a specific PIRT for a Loss of Coolant Accident (LOCA) especially where a break occurs at pipe in negative pressure (vacuum pressure) is presented in detail.

2. PIRT Methodology

The generic PIRT process is described in reference [3]. Based on generic PIRT process and other PIRT examples [4,5], the PIRT of thermal hydraulic phenomena for System Modular Advanced Reactor Technology (SMART) was developed [6]. We took the PIRT for SMART as a reference PIRT process and developed the PIRT process for RRs [2].

There are various design types of research reactor depending on purpose but typical design is open-pool type such as JRTR and KJRR. For this study, the KJRR is selected as a reference reactor for the PIR process since its design and operating characteristics show those in many pool type RRs.

3. Introduction of KiJang Research Reactors

The KiJang Research Reactor (KJRR) is an open-tank-in-pool type research reactor with power of 15 MW_{th}. Its main utilization purpose is to produce radioisotopes and provide the Neutron Transmutation Doping (NTD) service of Silicon [7].

The major Structures, Systems and Components (SSCs) of the KJRR are shown in Table I.

Table I. Structures, Systems, and Components of the KJRR

Structures / Systems	Components
Reactor Structure Assembly (RSA)	Core
Primary Cooling System (PCS)	PCS pipe
	PCS pumps (flywheel)
	Flap valves
	Siphon break valves
	Decay tank
Safety-related Residual Heat Removal System (SRHRS)	SRHRS pipe
	SRHRS pumps (flywheel)
Reactor Pool	Reactor pool

4. PIRT process

4.1. Figure of Merits

Given each scenario, all related phenomena that are of potential interest to an assessment are identified based on the figure of merit. The phenomena are ranked relative to their importance in predicting the figure of merit [8]. The selected FOMs are fuel performance criteria as below.

- Minimum Critical Heat Flux Ratio (MCHFR)
- Maximum Fuel Temperature (MFT)

4.2. LOCA scenario description

A LOCA can occur due to a rupture in the followings; 1) Pipes or components rupture in primary cooling system, 2) Systems connected to the pool or primary cooling system, 3) Pipes in penetration part of pool.

There are two scenarios for LOCA accidents, depending on the rupture position and the design of RR cooling system.

The first accident scenario is a typical LOCA in which coolant flows out of the cooling system when a pipe is ruptured.

The second LOCA scenario is a pipe rupture with negative pressure condition. Depending on the design of RR cooling system (generally in RRs with downward core flow), the internal pressure in some part of pipelines can be kept below atmospheric pressure during the normal operation. When a break occurs at pipe in negative pressure, the air can flow into the pipe inside. If the negative pressure in the pipe cannot be maintained, the coolant will leak out through the broken point.

A PIRT study herein deals with the second LOCA case which is a negative pressure pipe rupture.

4.2.1 Event sequence at a negative pressure pipe rupture

The phase I is from the initiation of the event to the point of reactor trip. When the pipe is ruptured, the air flows into the primary cooling system (PCS) pipe through the broken point and mixes with coolant in the pipe. The KJRR, a reference reactor for this study, has a large size of decay tank in the PCS for keeping the radioactive material for a certain period time. Therefore, when the air flows into the PCS, the air are stratified in the top of the decay tank and the pressure drop across the decay tank increases. As the decay tank differential pressure increases further, the reactor is tripped by the decay tank differential pressure high signal.

The phase II is until the safety residual heat removal system (SRHRS) pumps stop. When the PCS pumps are stopped by an operator or a stop signal after reactor trip, the flow rate and differential pressure through the core decrease with coastdown flow and the SRHRS pumps are activated. Since the flow rate of the SRHRS pump is lower than that of the PCS pump, the pressure inside the pipe cannot maintain lower than atmospheric pressure and the coolant starts to leak out through the broken area and the pool level decreases. As the pool level decreases further, the siphon break valves open and a coolant discharge is stopped by the siphon break phenomena.

The last III phase is natural convection cooling period. After SRHRS pumps stops, the flap valves open passively. The reactor core is then cooled by the natural circulation of the pool water via flap valves.

4.3. Phenomena Identification

Phenomena and phases identified for at the negative pressure pipe rupture are shown in Table II.

Table II. Phenomena and Phases

Comp.	Phenomena	Phase
Core	Core power	I, II, III
	Reactivity feedback	I, II, III
	Fuel heat transfer (conduction)	I, II, III
	Wall heat transfer - Single phase forced convection - Two phase forced convection - Natural convection	 I, II, III I, II, III III
	Flow reversal	III
	Wall friction	I, II, III
	Critical heat flux	I, II, III
PCS pipe	Two-phase flow (non-condensable gas and water flow)	I, II, III
	Critical flow (leak flow)	I, II, III
	Siphon break	I, II, III
Decay tank	Air-water separation	I, II, III
PCS pumps	Coastdown	II
SRHRS pumps	Coastdown	III
Reactor pool	Natural circulation - Thermal mixing - Natural circulation flow	III

4.4. Ranking

Table III shows the ranking criteria of phenomena importance and knowledge level. The rankings of importance of phenomenon and knowledge level are classified into High (H), Medium (M), and Low (L). Each phenomenon was evaluated on the basis of effects on the FOMs and databases, and rankings of importance and knowledge level were assigned. Table III shows the PIRT for the negative pressure pipe rupture.

Table III. Ranking criteria of Phenomena importance (P) and Knowledge level (K)

Ranking	Description
High (H)	(P) Significant influence on FOMs
	(K) Phenomenon is well known and can be accurately modeled
Medium (M)	(P) Moderate influence on FOMs
	(K) Phenomenon is understood, but can only be modeled with moderate uncertainty
Low (L)	(P) Small influence on FOMs
	(K) Phenomenon is very limitedly known. Modeling is currently either not possible or is possible only with large uncertainty

Core: The phenomena in the core are classified into the reactor kinetics related and the thermal hydraulic related. The effect of core power including decay heat is very significant to FOMs while the effect of reactivity feedback is not so significant because of little temperature variation before reactor trip. Several types of the convective heat transfer is very important phenomena, but the heat transfer phenomena except that in single phase in RR operational condition are partially known. The flow reversal is the flow direction change from downward forced flow to upward natural convection flow. The flow reversal is very important to FOMs because flow rate in the core becomes zero (stagnant) when flow reversal occurs after SRHRS pumps stop. CHF is one of the FOMs but the knowledge of CHF in research reactor is not enough.

PCS pipe: The phenomena in PCS pipes are very important for predicting air-inflow, mixture flow which flow into the decay tank, and water-outflow in phase II and III. However the behavior of air-water flow in RR condition is not well known.

Decay tank: The water-air mixture is separated in the decay tank. If water-air is not separated well in decay tank, air could enter into the pump and may reduce pump performance or cause damage. Since pump performance is very important to FOMs, air-water separation is a very important phenomenon but not well known.

PCS & SRHRS pumps: The coastdown flow rate is of importance to FOMs.

Reactor pool: The phenomena in the pool affects the FOMs in very limited manner.

Table III. PIRT for negative pressure pipe rupture

Comp.	Phenomena	Phenomenon rank by phase			State of knowledge
		I	II	III	
Core	Core power	H	H	H	H
	Reactivity feedback	M	L	L	H
	Fuel heat transfer (conduction)	M	L	L	H
	Single phase forced convection	H	H	H	H
	Two phase forced convection	H	H	H	M
	Natural convection	-	-	H	M
	Flow reversal	-	-	H	M
	Wall friction	H	H	H	H
	Critical heat flux	H	H	H	M
PCS pipe	Two phase flow (non-condensable gas and water flow)	H	H	L	L
	Critical flow (leak flow)	H	H	H	H
	Siphon break	H	H	H	M
Decay tank	Air-water seperation	H	H	L	L
PCS pumps	Coastdown	-	H	-	H
SRHRS pumps	Coastdown	-	-	H	H
Reactor pool	Thermal mixing	-	-	L	M
	Natural circulation flow	-	-	L	M

5. Conclusion

A PIRT process for the negative pressure pipe rupture has been performed. It is proposed from the results that the knowledge of phenomena listed below needs to be improved.

- Two phase forced convection under low pressure
- Natural convection and flow reversal
- Critical heat flux in narrow rectangular channel
- Non-condensable gas and water flow in PCS pipe
- Air-water separation in decay tank
- Siphon breaking

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