A LOEP Phenomena Identification and Ranking Tables (PIRTs) for Open-Tank-In-Pool Research Reactors

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1. Introduction

The nuclear safety of many research reactors has been ensured by a series of supporting analysis including safety analysis using thermal hydraulic system codes such as the legacy RELAP5 [1,2,3,4,5,6,7], developed at the Idaho National Engineering Laboratory (INEL) for the U.S. Nuclear Regulatory Commission (NRC) [8] and the CATHARE [9] developed for French power plant analysis.

Safety and Performance Analyzing Code (SPACE code) [10] for the analysis of nuclear power plants in Korea is being under consideration to apply for the safety analysis of research reactors (RRs).

The applicability of the SPACE code, licensed for Pressurized Water Reactors (PWRs) of high pressure and high temperature conditions, needs to be extended to cover the different operational conditions, for instance, the low pressure and low temperature conditions of research reactors [4].

For this purpose, a comprehensive and systematic approach such as Phenomena Identification and Ranking Tables (PIRT) [4, 11] is vital to facilitate the understanding of transient characteristics that may occur during the postulated events in RRs.

Included in this study are 1) typical RRs using material test reactor (MTR) type fuels [12], and 2) the JRTR [5] and the KJRR [6]. The KJRR is selected as a reference reactor for the PIR process.

A series of PIRTs was developed in order to characterize the challenges of the models for the accident analysis of the research reactors. In this paper, presented is only the part for a Loss of normal Electric Power (LOEP) scenario of the whole works [13] since the scenario covers most of the common phenomena.

2. PIRTs Methodology

A recent example of the PIRT process is a preliminary PIRT developed for System Modular Advanced ReacTor technology (SMART)-Pilot thermal-hydraulic phenomena in Korea [14]. The process applied to SMART-P T/H phenomena, which is also used in this study, is conceptually the same as the typical application [11], except that this study is differently categorized in more detail for developing ranking for systems, components, phenomena and processes, and knowledge-level.

3. Introduction to Research Reactors

RRs are very different from nuclear power plants in terms of design and operation as shown in table I [15]. Main features of RRs for this study are briefly summarized in table II [4,5,6,12].

Table I. Comparison of Characteristics between Research Reactors and Power Reactors

	Research Reactors	Power Reactors
Purpose	Production and R&D using neutron - High neutron flux	Electricity generation - High power production
Reactor type	Mostly Tank-in-pool type - Large coolant inventory for ultimate heat sink	Loop type - Small coolant inventory for heat sink
Power	0~30 MW_{th} for general RRs 40~250 MW_{th} for MTR	~ 3000 MW_{th}
Fuels	Metallic with high conductivity - Fuel alloy particles dispersed in Al	Ceramic fuel - High heat capacity
	Plate, tubular, finned rod type - Enhance heat removal	Rod type
Operating condition	Low pressure and low temperature - 1~10 bar, 20~50 °C	High pressure and high temperature - 150 bar, ~ 300 °C
System design	Relatively simple	Complicated
	But, core design is complicated due to test facilities	Strengthened safety features (e.g. ECCS)

3.1 KiJang Research Reactor

The KiJang Research Reactor (KJRR) is an open-tank-in-pool type research reactor with power of 15 MW_{th}, dedicated to neutron transmutation doping (NTD) of Si and the production of radioisotopes [4].

The reactor is operating at low pressure and low temperature conditions, similar to the JRTR, as shown in table II. There are apparently no different architectures from the JRTR except that the safety-related residual heat removal system (SRHRS) is added for cooling of the reactor just after shutting down of the reactor.

Table II. Major parameters of the JRTR, the KJRR, and other typical research reactors

	JRTR	KJRR	Other RRs
Purpose	Research and Training	Production of radioisotopes	Production of RIs Material Test
Reactor type	Open-tank-in-pool	Open-tank-in-pool	Open/Closed-tank-in-pool
	Downward flow	Downward flow	Downward/ Upward
Power [MW_{th}]	5, power mode 50 kW_{th} for training mode	15	Up to hundreds
Max. Heat flux [kW/m^2]	~ 500	~ 1300	Depends on designs ~ 3000
Mass flux [kg/m^2-s]	~ 3000	~ 6000	Depends on designs
Thermal N flux in core [neutrons/cm^2-s]	~ 1.5 x 10^{14}	~ 3.0 x 10^{14}	5 ~ 10 x 10^{14}
Fuels	Metallic U_3Si_2/Al	Metallic U-7Mo /Al-5Si	Depends on designs Metallic U
	19.75 wt% LEU	19.75 wt% LEU	~ 19.75 wt% LEU
	Plate type	Plate type	Plate or curved type
Operating condition	Low pressure and low temperature	Low pressure and low temperature	Depends on design Low/Medium pressure and low temperature
	~2 bar	~4 bar	~ tens bar,
	5~35°C	5~35°C	~50°C
System design	Relatively simple	Relatively simple	Comparable to nuclear power plants
	Passive safety systems	Active safety systems	

3.2 Other research reactors

Some other RRs are reviewed to identify representative characteristics focused on thermal hydraulics.

The major parameters for RRs with typical MTR fuels are given in table II [12]. Those reactors with generic MTR type fuels have generally modest heat flux and mass flux at low temperature condition. The KJRR is selected as a reference reactor for this PIR process since most of its design and operation parameters are in ranges similar to those of typical research reactors with moderate power level, generally speaking less than 30MW_{th}.

4. PIRT for a LOEP in Research Reactors

A typical sequence can be presented in the schematic of Fig. 1, which shows what phases may typically exist during any incident within most of the event sequences [16] for the reference reactor, KJRR. And Structures, Systems, and Components (SSCs) are given in table III.

Phase I

When an incident (a loss of normal electric power) occurs, cooling capability is abruptly lost because of pumps being off; however, coastdown flow keeps cooling the core for a certain period.

A reactor protection system (RPS) monitors and detects any occurrence of an incident from flow reduction. Shutdown system insert automatically the control rods due to the cut-off of electric power to the rods.

As soon as control rods drop into the core, the power is reduced to the extent that decay power only needs to be continuously cooled down and the core maintains sub-criticality.

Phase II

A safety-related residual heat removal system (SRHRS), which may be selected depending on the decay power level of a reactor and is applied in the KJRR, starts to cool the core following the coastdown flow after primary pumps off during a LOEP.

Phase III

After the core power is sufficiently reduced, the SRHRS pumps stop, and the flap valves are passively opened by the pump stop; core flow direction changes from downward to upward (so-called flow reversal occurs in the core). Afterwards, pool water natural circulation through the SSCs such as the core and flap valves plays a major role in cooling the core.

Phase IV

Nuclear safety must be ensured during long term cooling (LTC), during which the reactor is not used or just held for planned maintenance.

4.1. Scenario description

A loss of normal electric power (LOEP) can occur due to electric load trouble such as an overload in the system buses. The event scenario of a LOEP can be divided into three phases according to changes in the reactor behavior with time, as given in Fig. 1. If normal electric power is lost for a long time, the event sequence can be extended to phase IV.

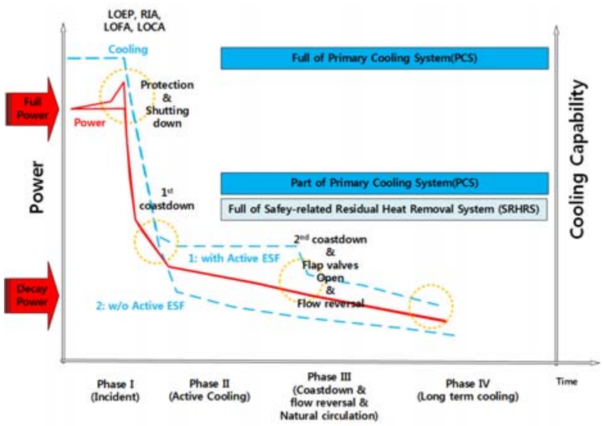

Fig. 1. Schematic on main sequence of all the events within Design Extension Conditions of the KJRR

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

Structures / Systems	Components
Reactor Structure Assembly (RSA)	Reactor core (fuels)
	Reactor core (coolant)
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

4.2. Phenomena Identification

Dominant thermal hydraulic phenomena in the reactor core are very similar in phases I and II. In these phases, the coolant flow through the reactor core is downward and the decay heat is cooled by single phase forced convection flow. After flow reversal occurs in the reactor core during phase III, the decay heat is cooled by single phase natural convective cooling of the pool water. In this phase, relatively strong thermal mixing compared to that in phases I and II can take place in the reactor pool due to the establishment of 3-dimensional natural circulation through flap valves, reactor core, and reactor pool, sequentially. The dominant thermal hydraulic phenomena for the major components during a LOEP are summarized in table IV.

4.3. Ranking (Importance & Knowledge)

Not well known compared to its essentially high importance rank is CHF at a narrow rectangular channel in a typical RR with plate-type fuels. It holds for CHF in phase III, particularly at the moment of flow stagnation in the course of flow reversal in the cooling channel. The knowledge level is high enough for a sufficiently satisfactory margin to be quantified.

Wall heat transfer between the fuel surface and the coolant is the dominant factor affecting the figure of merit in the KJRR, such as CHF and fuel temperature, although other thermal hydraulic factors including the decay heat and flow rate through the core also have relatively large and direct impact on CHF and fuel temperature. Appropriate heat transfer coefficients for single phase forced and natural convection are important to accurately predict the temperatures of fuel and coolant in the reactor core.

The flow rate through the reactor core, which is determined by 1) coastdown flow of the PCS pumps, 2) coastdown flow of the SRHRS pumps, and 3) the buoyancy force driven by the core residual heat during phase I, phase II, and phase III, is next in priority of importance of thermal hydraulic phenomena.

A summary of the ranking of importance and knowledge of phenomena during an LOEP is shown in table V.

Table IV. Major thermal hydraulic phenomena for major components during a LOEP

(a) Reactor Structure Assembly

Comp.	Phenomena	Description
Rx core (fuel)	Energy generation rate in the fuels	Heat generation rate due to accumulation of the fission products and actinides at steady-state or at shutdown during any incident (decay power)
	Reactivity feedback	The core power depends on the reactivity feedback owing to the fuel and moderate (coolant) temperature variations.
	Fuel heat transfer(conduction)	The conduction affects temperature distribution in a fuel.
Rx core (coolant)	Critical heat flux (CHF)	The CHF is the most paramount factor in determining fuel integrity.
	Flow reversal	The decay heat at the time of flow reversal in the reactor core is important as a heat source to be removed at that moment.

(b) PCS & SRHRS

Comp.	Phenomena	Description
PCS pipe	Forced convective flow	The forced flow is formed in the PCS pipe during phase I and II.
	Natural	The natural circulation flow is

	circulation flow	established in some section of the PCS pipe (from flap valve to the part of PCS pipe connected to lower plenum) during phase III and IV.

(c) Pool

Comp.	Phenomena	Description
Reactor pool	Natural circulation (flap valve-core-pool)	Both the thermal mixing the natural circulation flow rate affects the temperature distribution in a reactor pool during phase III.

Table V. Result of the PIRT for a LOEP

(a) Reactor Structure Assembly

Comp.	Phenomena	Phenomena rank by phase			State of knowledge
		I	II	III	
Reactor core (fuel)	Energy generation rate in the fuel	H	H	H	H
	Reactivity feedback	M	L	L	H
	Fuel heat transfer (conduction)	M	L	L	H
Reactor core (coolant)	CHF	H	H	H	M
	Wall heat transfer (single-phase forced convection)	H	H	-	H
	Wall heat transfer (single-phase natural convection)	-	-	H	M
	Wall heat transfer (two-phase forced convection)	H	-	-	M
	Wall friction	H	H	H	H
	Flow reversal	-	-	H	M

(b) PCS & SRHRS

Comp.	Phenomena	Phenomena rank by phase			State of knowledge
		I	II	III	
PCS pump (flywheel)	Coastdown	H	L	-	H
SRHRS pump (flywheel)	Coastdown	-	-	H	H

(c) Pool

Comp.	Phenomena	Phenomena rank by phase			State of knowledge
		I	II	III	
Reactor pool	Natural circulation (flap valve-core-pool)	-	-	M	M
	Thermally mixing by multi-dimensional flow	L	L	L	M

5. Conclusion

A PIRT study was performed to extend the applicability of the SPACE code, a newly licensed code of Korea for nuclear power plants to RRs, focused on the thermal hydraulics of the reference reactor, i.e., the KJRR, covering TH phenomena in most typical research reactors rated up to medium power (~ several tens of megawatts).

Only part of a LOEP among the various event scenarios but most of the common phenomena that could be possibly postulated in typical research reactors was presented in this paper.

It is proposed that further research be carried out to increase knowledge level and to improve current research reactor design, in order of importance as below:

1. critical heat flux during flow reversal;
2. multi-dimensional mixing in pool;

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